The Fukushima Daiichi Accident

Report by the Director General

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THE FUKUSHIMA DAIICHI ACCIDENT

REPORT BY THE DIRECTOR GENERAL

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world''.

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FOREWORD

By Yukiya Amano
Director General

This report presents an assessment of the causes and consequences of the accident at the Fukushima Daiichi nuclear power plant in Japan, which began on 11 March 2011. Caused by a huge tsunami that followed a massive earthquake, it was the worst accident at a nuclear power plant since the Chernobyl disaster in 1986.

The report considers human, organizational and technical factors, and aims to provide an understanding of what happened, and why, so that the necessary lessons learned can be acted upon by governments, regulators and nuclear power plant operators throughout the world. Measures taken in response to the accident, both in Japan and internationally, are also examined.

The immense human impact of the Fukushima Daiichi accident should not be forgotten. More than 100 000 people were evacuated because of the release of radionuclides to the environment. At the time of writing, in 2015, many of them were still unable to return to their homes.

I visited the Fukushima Daiichi plant a few months after the accident and saw for myself the powerful and destructive impact of the tsunami. It was a shocking and sobering experience.

But I was deeply impressed by the courage and dedication of those workers and managers who remained at their posts after the tsunami struck and who struggled, in appalling conditions, to bring the stricken reactors under control. They had to improvise a response in circumstances for which they had not been trained, often lacking appropriate equipment. They deserve our respect and admiration.

A major factor that contributed to the accident was the widespread assumption in Japan that its nuclear power plants were so safe that an accident of this magnitude was simply unthinkable. This assumption was accepted by nuclear power plant operators and was not challenged by regulators or by the Government. As a result, Japan was not sufficiently prepared for a severe nuclear accident in March 2011.

The Fukushima Daiichi accident exposed certain weaknesses in Japan's regulatory framework. Responsibilities were divided among a number of bodies, and it was not always clear where authority lay.

There were also certain weaknesses in plant design, in emergency preparedness and response arrangements and in planning for the management of a severe accident. There was an assumption that there would never be a loss of all electrical power at a nuclear power plant for more than a short period. The possibility of several reactors at the same facility suffering a crisis at the same time was not considered. And insufficient provision was made for the possibility of a nuclear accident occurring at the same time as a major natural disaster.

Since the accident, Japan has reformed its regulatory system to better meet international standards. It gave regulators clearer responsibilities and greater authority. The new regulatory framework will be reviewed by international experts through an IAEA Integrated Regulatory Review Service mission. Emergency preparedness and response arrangements have also been strengthened.

Other countries responded to the accident with measures that included carrying out 'stress tests' to reassess the design of nuclear power plants against site specific extreme natural hazards, installing additional backup sources of electrical power and supplies of water, and strengthening the protection of plants against extreme external events.

Although nuclear safety remains the responsibility of each individual country, nuclear accidents can transcend national borders. The Fukushima Daiichi accident underlined the vital importance of effective international cooperation. The IAEA is where most of that cooperation takes place. Our Member States adopted the IAEA Action Plan on Nuclear Safety a few months after the accident and have been implementing its far-reaching provisions to improve global nuclear safety.

The IAEA, which provided technical support and expertise to Japan after the accident and shared information about the unfolding crisis with the world, has reviewed and improved its own arrangements for responding to a nuclear emergency. Our role during a nuclear emergency has been expanded to include providing analysis of its potential consequences and presenting possible scenarios on how a crisis could develop.

IAEA safety standards embody an international consensus on what constitutes a high level of safety. They were reviewed after the accident by the Commission on Safety Standards. A few amendments were proposed and adopted. I encourage all countries to fully implement IAEA safety standards.

IAEA peer reviews have a key role to play in global nuclear safety, enabling countries to benefit from the independent insights of leading international experts, based on the common reference frame of the IAEA safety standards. They address issues such as operational safety at nuclear power plants, the effectiveness of nuclear regulators and the design of nuclear power plant sites against specific hazards. We have strengthened our peer review programme since the accident and will continue to do so.

I am confident that the legacy of the Fukushima Daiichi accident will be a sharper focus on nuclear safety everywhere. I have seen improvements in safety measures and procedures in every nuclear power plant that I have visited. There is widespread recognition that everything humanly possible must be done to ensure that no such accident ever happens again. This is all the more essential as global use of nuclear power is likely to continue to grow in the coming decades.

There can be no grounds for complacency about nuclear safety in any country. Some of the factors that contributed to the Fukushima Daiichi accident were not unique to Japan. Continuous questioning and openness to learning from experience are key to safety culture and are essential for everyone involved in nuclear power. Safety must always come first.

I express my gratitude to the experts from many countries and international organizations who contributed to this report, and to my colleagues at the IAEA who drafted and reviewed it. I hope that the report, and the accompanying technical volumes, will prove valuable to all countries that use, or plan to use, nuclear power in their continuous efforts to improve safety.

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Financial assistance was provided by Canada, Japan, the Russian Federation, the United Kingdom and the United States of America.

In-kind contributions were received from Argentina, Australia, Belarus, Brazil, Canada, China, Cuba, the Czech Republic, Finland, France, Germany, Ghana, Iceland, India, Indonesia, Israel, Italy, Japan, the Republic of Korea, Malaysia, Mexico, Morocco, the Netherlands, New Zealand, Norway, Pakistan, the Philippines, Poland, the Russian Federation, Slovakia, South Africa, Spain, Sweden, Switzerland, the Syrian Arab Republic, Turkey, Ukraine, the United Arab Emirates, the United Kingdom, the United Republic of Tanzania and the United States of America. In-kind contributions were also received from the European Commission, the Food and Agriculture Organization of the United Nations, the International Commission on Radiological Protection, the International Labour Organization, the International Nuclear Safety Group, the OECD Nuclear Energy Agency, the United Nations Scientific Committee on the Effects of Atomic Radiation, the World Association of Nuclear Operators and the World Meteorological Organization.

The Government of Japan provided invaluable support by making available a considerable amount of information, arranging for Japanese experts to support the work on the report and ensuring logistical assistance for bilateral meetings in Japan.

The United Nations Scientific Committee on the Effects of Atomic Radiation supported the IAEA by sharing the relevant database of references from its 2013 report and allowing information and figures from the report to be reproduced.

The IAEA thanks the large number of experts who were involved in this report. It is the result of the dedicated efforts of many people. All participants listed at the end of this report made valuable contributions, but a particularly heavy load was borne by the Co-Chairs and coordinators of the working groups. The efforts of many expert reviewers, including members of the International Technical Advisory Group, are also gratefully acknowledged.

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EXECUTIVE SUMMARY

The Great East Japan Earthquake occurred on 11 March 2011. It was caused by a sudden release of energy at the interface where the Pacific tectonic plate forces its way under the North American tectonic plate. A section of the Earth's crust, estimated to be about 500 km in length and 200 km wide, was ruptured, causing a massive earthquake with a magnitude of 9.0 and a tsunami which struck a wide area of coastal Japan, including the north-eastern coast, where several waves reached heights of more than ten metres. The earthquake and tsunami caused great loss of life and widespread devastation in Japan. More than 15 000 people were killed, over 6000 were injured and, at the time of writing of this report[1], around 2500 people were still reported to be missing. Considerable damage was caused to buildings and infrastructure, particularly along Japan's north-eastern coast.

At the Fukushima Daiichi nuclear power plant, operated by the Tokyo Electric Power Company (TEPCO), the earthquake caused damage to the electric power supply lines to the site, and the tsunami caused substantial destruction of the operational and safety infrastructure on the site. The combined effect led to the loss of off-site and on-site electrical power. This resulted in the loss of the cooling function at the three operating reactor units[2] as well as at the spent fuel pools. The four other nuclear power plants[3] along the coast were also affected to different degrees by the earthquake and tsunami. However, all operating reactor units at these plants were safely shut down.

Despite the efforts of the operators at the Fukushima Daiichi nuclear power plant to maintain control, the reactor cores in Units 1–3 overheated, the nuclear fuel melted and the three containment vessels were breached. Hydrogen was released from the reactor pressure vessels, leading to explosions inside the reactor buildings in Units 1, 3 and 4 that damaged structures and equipment and injured personnel. Radionuclides were released from the plant to the atmosphere and were deposited on land and on the ocean. There were also direct releases into the sea.

People within a radius of 20 km of the site and in other designated areas were evacuated, and those within a radius of 20–30 km were instructed to shelter before later being advised to voluntarily evacuate. Restrictions were placed on the distribution and consumption of food and the consumption of drinking water. At the time of writing, many people were still living outside the areas from which they were evacuated.

Following stabilization of the conditions of the reactors at the Fukushima Daiichi nuclear power plant[4], work to prepare for their eventual decommissioning began. Efforts towards the recovery of the areas affected by the accident, including remediation and the revitalization of communities and infrastructure, began in 2011.

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[1] March 2015. In some cases, information was available up to June 2015 and has been included, where possible.

[2] Of the six units of the Fukushima Daiichi nuclear power plant, Units 1, 2 and 3 were operating at the time of the accident; Units 4, 5 and 6 were in planned shutdown.

[3] The Higashidori, Onagawa, Fukushima Daini and Tokai Daini nuclear power plants.

[4] On 16 December 2011, the Government–TEPCO Integrated Response Office announced that the conditions for a 'cold shutdown state' had been achieved in Units 1–3. The term 'cold shutdown state' was defined by the Government of Japan at the time specifically for the Fukushima Daiichi nuclear power plant. Its definition differs from the terminology used by the IAEA and others.

In the immediate aftermath of the accident, the IAEA discharged its emergency response role. It activated its Incident and Emergency System, coordinated the inter-agency response and initiated a series of briefings with Member States and the media.

The Director General visited Japan immediately and the IAEA dispatched several missions to Japan, including an international fact finding mission and peer review missions on decommissioning and remediation.

The IAEA organized an International Ministerial Conference on Nuclear Safety in June 2011, which resulted in a Ministerial Declaration on Nuclear Safety. This declaration outlined a number of measures to further improve nuclear safety, emergency preparedness and radiation protection of people and the environment worldwide. It also expressed the firm commitment of IAEA Member States to ensure that these measures were taken.

The Ministerial Declaration also requested the Director General to prepare a draft IAEA Action Plan on Nuclear Safety (the Action Plan)[5], in consultation with Member States. The Action Plan, which defined a programme of work to strengthen the global nuclear safety framework, was unanimously endorsed by the 55th IAEA General Conference in 2011.

The IAEA also undertook cooperative activities in Fukushima through a memorandum of cooperation between the IAEA and Fukushima Prefecture. This provided the basis for cooperation on radiation monitoring and remediation, human health, and emergency preparedness and response.

The IAEA also facilitated and organized a number of international conferences and meetings of its Member States and the Contracting Parties to the Convention on Nuclear Safety. Many of these activities took place under the Action Plan.

Since the accident at the Fukushima Daiichi nuclear power plant, there have been many analyses of its causes and consequences, as well as detailed considerations of its implications for nuclear safety, by IAEA Member States and international organizations and by States party to international nuclear safety instruments, in particular the Convention on Nuclear Safety. An extraordinary meeting of the Contracting Parties to the Convention on Nuclear Safety was held in August 2012 to review and discuss the initial analyses of the accident and the effectiveness of the Convention.

The Contracting Parties to the Convention on Nuclear Safety, at the 6th Review Meeting in March–April 2014, reported on the implementation of safety upgrades, including: the introduction of additional means to withstand prolonged loss of power and cooling; the enhancement of power systems to improve reliability; the re-evaluation of site specific external natural hazards and multi-unit events; the improvements of on-site and off-site emergency control centres to ensure protection from extreme external events and radiation hazards; the strengthening of measures to preserve containment integrity; and the improvement of severe accident management provisions and guidelines.

In February 2015, the Contracting Parties to the Convention on Nuclear Safety, at a Diplomatic Conference convened by the IAEA Director General, adopted the Vienna Declaration on Nuclear Safety, which includes principles for the implementation of the third objective of the Convention,

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[5] The Action Plan defined a programme of work to strengthen the global nuclear safety framework. The Action Plan consists of 12 main actions related to: safety assessments; IAEA peer reviews; emergency preparedness and response; national regulatory bodies; operating organizations; IAEA safety standards; the international legal framework; Member States planning to embark on a nuclear power programme; capacity building; the protection of people and the environment from ionizing radiation; communication and information dissemination; and research and development. For more details, see Section 6.1.

which is to prevent accidents with radiological consequences and to mitigate such consequences should they occur.

THE REPORT ON THE FUKUSHIMA DAIICHI ACCIDENT

At the IAEA General Conference in September 2012, the Director General announced that the IAEA would prepare a report on the Fukushima Daiichi accident. He later stated that this would be “an authoritative, factual and balanced assessment, addressing the causes and consequences of the accident, as well as lessons learned”.

The report on the Fukushima Daiichi accident is the result of an extensive international collaborative effort involving five working groups with about 180 experts from 42 Member States (with and without nuclear power programmes) and several international bodies. This ensured a broad representation of experience and knowledge. An International Technical Advisory Group provided advice on technical and scientific issues. A Core Group, comprising IAEA senior level management, was established to give direction and to facilitate the coordination and review of the report. Additional internal and external review mechanisms were also instituted.

This Report by the Director General consists of an Executive Summary and a Summary Report. It draws on five detailed technical volumes prepared by international experts and on the contributions of the many experts and international bodies involved. The report provides a description of the accident and its causes, evolution and consequences, based on the evaluation of data and information from a large number of sources available up to March 2015, including the results of the work carried out in implementing the Action Plan, and it highlights the main observations and lessons. Significant amounts of data were provided by the Government of Japan and other organizations in Japan.

NUCLEAR SAFETY CONSIDERATIONS

Vulnerability of the plant to external events

The earthquake on 11 March 2011 caused vibratory ground motions, which shook the plant structures, systems and components. It was followed by a series of tsunami waves, one of which inundated the site. Both the recorded ground motions and the heights of the tsunami waves significantly exceeded the assumptions of hazards that had been made when the plant was originally designed. The earthquake and the associated tsunami impacted on multiple units at the Fukushima Daiichi nuclear power plant.

The seismic hazard and tsunami waves considered in the original design were evaluated mainly on the basis of historical seismic records and evidence of recent tsunamis in Japan. This original evaluation did not sufficiently consider tectonic-geological criteria, and no re-evaluation using such criteria was conducted.

Prior to the earthquake, the Japan Trench was categorized as a subduction zone with a frequent occurrence of magnitude 8 class earthquakes; an earthquake of magnitude 9.0 off the coast of Fukushima Prefecture was not considered to be credible by Japanese scientists. However, similar or higher magnitudes had been registered in different areas in similar tectonic environments in the past few decades.

There were no indications that the main safety features of the plant were affected by the vibratory ground motions generated by the earthquake on 11 March 2011. This was due to the conservative approach to earthquake design and construction of nuclear power plants in Japan, resulting in a plant that was provided with sufficient safety margins. However, the original design considerations did not provide comparable safety margins for extreme external flooding events, such as tsunamis.

The vulnerability of the Fukushima Daiichi nuclear power plant to external hazards had not been reassessed in a systematic and comprehensive manner during its lifetime. At the time of the accident, there were no regulatory requirements in Japan for such reassessments, and relevant domestic and international operating experience was not adequately considered in the existing regulations and guidelines. The regulatory guidelines in Japan on methods for dealing with the effects of events associated with earthquakes, such as tsunamis, were generic and brief, and did not provide specific criteria or detailed guidance.

Before the accident, the operator had conducted some reassessments of extreme tsunami flood levels, using a consensus based methodology developed in Japan in 2002, which had resulted in values higher than the original design basis estimates. Based on the results, some compensatory measures were taken, but they proved to be insufficient at the time of the accident.

In addition, a number of trial calculations were performed by the operator before the accident, using wave source models or methodologies that went beyond the consensus based methodology. Thus, a trial calculation using the source model proposed by the Japanese Headquarters for Earthquake Research Promotion in 2002, which used the latest information and took a different approach in its scenarios, envisaged a substantially larger tsunami than that provided for in the original design and in estimates made in previous reassessments. At the time of the accident, further evaluations were being conducted, but in the meantime, no additional compensatory measures were implemented. The estimated values were similar to the flood levels recorded in March 2011.

Worldwide operating experience has shown instances where natural hazards have exceeded the design basis for a nuclear power plant. In particular, the experience from some of these events demonstrated the vulnerability of safety systems to flooding.

— **The assessment of natural hazards needs to be sufficiently conservative. The consideration of mainly historical data in the establishment of the design basis of nuclear power plants is not sufficient to characterize the risks of extreme natural hazards. Even when comprehensive data are available, due to the relatively short observation periods, large uncertainties remain in the prediction of natural hazards.**
— **The safety of nuclear power plants needs to be re-evaluated on a periodic basis to consider advances in knowledge, and necessary corrective actions or compensatory measures need to be implemented promptly.**
— **The assessment of natural hazards needs to consider the potential for their occurrence in combination, either simultaneously or sequentially, and their combined effects on a nuclear power plant. The assessment of natural hazards also needs to consider their effects on multiple units at a nuclear power plant.**
— **Operating experience programmes need to include experience from both national and international sources. Safety improvements identified through operating experience programmes need to be implemented promptly. The use of operating experience needs to be evaluated periodically and independently.**

Application of the defence in depth concept

Defence in depth is a concept that has been applied to ensure the safety of nuclear installations since the start of nuclear power development. Its objective is to compensate for potential human and equipment failures by means of several levels of protection. Defence is provided by multiple and independent means at each level of protection.

The design of the Fukushima Daiichi nuclear power plant provided equipment and systems for the first three levels of defence in depth: (1) equipment intended to provide reliable normal operation; (2) equipment intended to return the plant to a safe state after an abnormal event; and (3) safety systems intended to manage accident conditions. The design bases were derived using a range of postulated hazards; however, external hazards such as tsunamis were not fully addressed. Consequently, the flooding resulting from the tsunami simultaneously challenged the first three protective levels of defence in depth, resulting in common cause failures of equipment and systems at each of the three levels.

The common cause failures of multiple safety systems resulted in plant conditions that were not envisaged in the design. Consequently, the means of protection intended to provide the fourth level of defence in depth, that is, prevention of the progression of severe accidents and mitigation of their consequences, were not available to restore the reactor cooling and to maintain the integrity of the containment. The complete loss of power, the lack of information on relevant safety parameters due to the unavailability of the necessary instruments, the loss of control devices and the insufficiency of operating procedures made it impossible to arrest the progression of the accident and to limit its consequences.

The failure to provide sufficient means of protection at each level of defence in depth resulted in severe reactor damage in Units 1, 2 and 3 and in significant radioactive releases from these units.

— **The defence in depth concept remains valid, but implementation of the concept needs to be strengthened at all levels by adequate independence, redundancy, diversity and protection against internal and external hazards. There is a need to focus not only on accident prevention, but also on improving mitigation measures.**
— **Instrumentation and control systems that are necessary during beyond design basis accidents need to remain operable in order to monitor essential plant safety parameters and to facilitate plant operations.**

Assessment of the failure to fulfil fundamental safety functions

The three fundamental safety functions important for ensuring safety are: the control of reactivity in the nuclear fuel; the removal of heat from the reactor core and spent fuel pool; and the confinement of radioactive material. Following the earthquake, the first fundamental safety function — control of reactivity — was fulfilled in all six units at the Fukushima Daiichi nuclear power plant.

The second fundamental safety function — removing heat from the reactor core and the spent fuel pool — could not be maintained because the operators were deprived of almost all means of control over the reactors of Units 1, 2 and 3 and the spent fuel pools as a result of the loss of most of the AC and DC electrical systems. The loss of the second fundamental safety function was, in part, due to the failure to implement alternative water injection because of delays in depressurizing the reactor pressure vessels. Loss of cooling led to overheating and melting of the fuel in the reactors.

The confinement function was lost as a result of the loss of AC and DC power, which rendered the cooling systems unavailable and made it difficult for the operators to use the containment venting system. Venting of the containment was necessary to relieve pressure and prevent its failure. The operators were able to vent Units 1 and 3 to reduce the pressure in the primary containment vessels. However, this resulted in radioactive releases to the environment. Even though the containment vents for Units 1 and 3 were opened, the primary containment vessels for Units 1 and 3 eventually failed. Containment venting for Unit 2 was not successful, and the containment failed, resulting in radioactive releases.

- **Robust and reliable cooling systems that can function for both design basis and beyond design basis conditions need to be provided for the removal of residual heat.**
- **There is a need to ensure a reliable confinement function for beyond design basis accidents to prevent significant release of radioactive material to the environment.**

Assessment of beyond design basis accidents and accident management

Safety analyses conducted during the licensing process of the Fukushima Daiichi nuclear power plant, and during its operation, did not fully address the possibility of a complex sequence of events that could lead to severe reactor core damage. In particular, the safety analyses failed to identify the vulnerability of the plant to flooding and weaknesses in operating procedures and accident management guidelines. The probabilistic safety assessments did not address the possibility of internal flooding, and the assumptions regarding human performance for accident management were optimistic. Furthermore, the regulatory body had imposed only limited requirements for operators to consider the possibility of severe accidents.

The operators were not fully prepared for the multi-unit loss of power and the loss of cooling caused by the tsunami. Although TEPCO had developed severe accident management guidelines, they did not cover this unlikely combination of events. Operators had therefore not received appropriate training and had not taken part in relevant severe accident exercises, and the equipment available to them was not adequate in the degraded plant conditions.

In September 2012, the Nuclear Regulation Authority (NRA) was established. The NRA formulated new regulations for nuclear power plants to protect the people and the environment, which came into force in 2013. These regulations strengthened countermeasures to prevent simultaneous loss of all safety functions due to common causes, including re-evaluation of the impact of external events such as earthquakes and tsunamis. New countermeasures for severe accident response against core damage, containment vessel damage and a diffusion of radioactive material were also introduced.

- **Comprehensive probabilistic and deterministic safety analyses need to be performed to confirm the capability of a plant to withstand applicable beyond design basis accidents and to provide a high degree of confidence in the robustness of the plant design.**
- **Accident management provisions need to be comprehensive, well designed and up to date. They need to be derived on the basis of a comprehensive set of initiating events and plant conditions and also need to provide for accidents that affect several units at a multi-unit plant.**
- **Training, exercises and drills need to include postulated severe accident conditions to ensure that operators are as well prepared as possible. They need to include the simulated use of actual equipment that would be deployed in the management of a severe accident.**

Assessment of regulatory effectiveness

The regulation of nuclear safety in Japan at the time of the accident was performed by a number of organizations with different roles and responsibilities and complex inter-relationships. It was not fully clear which organizations had the responsibility and authority to issue binding instructions on how to respond to safety issues without delay.

The regulatory inspection programme was rigidly structured, which reduced the regulatory body's ability to verify safety at the proper times and to identify potential new safety issues.

The regulations, guidelines and procedures in place at the time of the accident were not fully in line with international practice in some key areas, most notably in relation to periodic safety reviews, re-evaluation of hazards, severe accident management and safety culture.

— **In order to ensure effective regulatory oversight of the safety of nuclear installations, it is essential that the regulatory body is independent and possesses legal authority, technical competence and a strong safety culture.**

Assessment of human and organizational factors

Before the accident, there was a basic assumption in Japan that the design of nuclear power plants and the safety measures that had been put in place were sufficiently robust to withstand external events of low probability and high consequences.

Because of the basic assumption that nuclear power plants in Japan were safe, there was a tendency for organizations and their staff not to challenge the level of safety. The reinforced basic assumption among the stakeholders about the robustness of the technical design of nuclear power plants resulted in a situation where safety improvements were not introduced promptly.

The accident at the Fukushima Daiichi nuclear power plant showed that, in order to better identify plant vulnerabilities, it is necessary to take an integrated approach that takes account of the complex interactions between people, organizations and technology.

— **In order to promote and strengthen safety culture, individuals and organizations need to continuously challenge or re-examine the prevailing assumptions about nuclear safety and the implications of decisions and actions that could affect nuclear safety.**
— **A systemic approach to safety needs to consider the interactions between human, organizational and technical factors. This approach needs to be taken through the entire life cycle of nuclear installations.**

EMERGENCY PREPAREDNESS AND RESPONSE

Initial response in Japan to the accident

At the time of the accident, separate arrangements were in place to respond to nuclear emergencies and natural disasters at the national and local levels. There were no coordinated arrangements for responding to a nuclear emergency and a natural disaster occurring simultaneously.

The arrangements to respond to nuclear emergencies envisaged that, following the detection of relevant adverse conditions at a nuclear power plant (e.g. loss of all AC power supplies for more than five minutes or loss of all capabilities to cool the reactor), a notification would be sent from the plant to local and national governments. The national Government would then assess the situation and determine whether it was to be categorized as a 'nuclear emergency'[6]. If the situation was categorized as a nuclear emergency, a declaration to that effect would be issued at the national level, and decisions about necessary protective actions would be taken on the basis of dose projections.

Based on a report from the Fukushima Daiichi nuclear power plant, the Prime Minister declared a nuclear emergency on the evening of 11 March and issued orders for protective actions for the public. The response at the national level was led by the Prime Minister and senior officials at the Prime Minister's Office in Tokyo.

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[6] Act on Special Measures Concerning Nuclear Emergency Preparedness, Act No. 156 of 1999, as last amended by Act No. 118 of 2006, hereinafter referred to as the Nuclear Emergency Act.

The consequences of the earthquake and tsunami, and increased radiation levels, made the on-site response extremely difficult. The loss of AC and DC electrical power, the presence of a huge amount of rubble that hindered on-site response measures, aftershocks, alerts of further tsunamis and increased radiation levels meant that many mitigatory actions could not be carried out in a timely manner. The national Government was involved in decisions concerning mitigatory action on the site.

The activation of the emergency Off-site Centre, located 5 km from the Fukushima Daiichi nuclear power plant, was difficult because of extensive infrastructure damage caused by the earthquake and tsunami. Within a few days, it became necessary to evacuate the Off-site Centre due to adverse radiological conditions.

— **In preparing for the response to a possible nuclear emergency, it is necessary to consider emergencies that could involve severe damage to nuclear fuel in the reactor core or to spent fuel on the site, including those involving several units at a multi-unit plant possibly occurring at the same time as a natural disaster.**
— **The emergency management system for response to a nuclear emergency needs to include clearly defined roles and responsibilities for the operating organization and for local and national authorities. The system, including the interactions between the operating organization and the authorities, needs to be regularly tested in exercises.**

Protecting emergency workers

At the time of the accident, the national legislation and guidance in Japan addressed measures to be taken for the protection of emergency workers, but only in general terms and not in sufficient detail.

Many emergency workers from different professions were needed to support the emergency response. Emergency workers came from various organizations and public services. However, there were no arrangements in place to integrate into the response those emergency workers who had not been designated prior to the accident.

Implementation of the arrangements for ensuring the protection of workers against radiation exposure was severely affected by the extreme conditions at the site. In order to maintain an acceptable level of protection for on-site emergency workers, a range of impromptu measures was implemented. The dose limit for emergency workers undertaking specific tasks was temporarily increased to allow the necessary mitigatory actions to continue. Medical management of emergency workers was also severely affected, and major efforts were required to meet the needs of on-site emergency workers.

Members of the public, referred to as 'helpers', volunteered to assist in the off-site emergency response. National authorities issued guidance on the type of activities that helpers could carry out and on measures to be taken for their protection.

— **Emergency workers need to be designated, assigned clearly specified duties, regardless of which organization they work for, be given adequate training and be properly protected during an emergency. Arrangements need to be in place to integrate into the response those emergency workers who had not been designated prior to the emergency, and helpers who volunteer to assist in the emergency response.**

Protecting the public

National emergency arrangements at the time of the accident envisaged that decisions on protective actions would be based on estimates of the projected dose to the public that would be calculated when a decision was necessary, using a dose projection model — the System for Prediction of Environmental Emergency Dose Information (SPEEDI). The arrangements did not envisage that decisions on urgent protective actions for the public would be based on predefined specific plant conditions. However, in response to the accident, the initial decisions on protective actions were made on the basis of plant conditions. Estimates of the source term could not be provided as an input to SPEEDI owing to the loss of on-site power.

The arrangements prior to the accident included criteria for sheltering, evacuation and iodine thyroid blocking in terms of projected dose, but not in terms of measurable quantities. There were no criteria for relocation.

Protective actions for the public implemented during the accident included: evacuation; sheltering; iodine thyroid blocking (through the administration of stable iodine); restrictions on the consumption of food and drinking water; relocation; and the provision of information.

The evacuation of people from the vicinity of the Fukushima Daiichi nuclear power plant began in the evening of 11 March 2011, with the evacuation zone gradually extended from a radius of 2 km of the plant to 3 km and then to 10 km. By the evening of 12 March, it had been extended to 20 km. Similarly, the area in which people were ordered to shelter was extended from within 3–10 km of the plant shortly after the accident to within 20–30 km by 15 March. In the area within a 20–30 km radius of the nuclear power plant, the public was ordered to shelter until 25 March, when the national Government recommended voluntary evacuation. Administration of stable iodine for iodine thyroid blocking was not implemented uniformly, primarily due to the lack of detailed arrangements.

There were difficulties in evacuation due to the damage caused by the earthquake and tsunami and the resulting communication and transportation problems. There were also significant difficulties encountered when evacuating patients from hospitals and nursing homes within the 20 km evacuation zone.

On 22 April, the existing 20 km evacuation zone was established as a ‘Restricted Area’, with controlled re-entry. A ‘Deliberate Evacuation Area’ was also established beyond the ‘Restricted Area’ in locations where the specific dose criteria for relocation might be exceeded.

Once radionuclides were detected in the environment, arrangements were made regarding protective actions in the agricultural area and restrictions on the consumption and distribution of food and consumption of drinking water. In addition, a certification system for food and other products intended for export was established.

Several channels were used to keep the public informed and to respond to people’s concerns during the emergency, including television, radio, the Internet and telephone hotlines. Feedback from the public received via hotlines and counselling services identified the need for easily understandable information and supporting material.

— **Arrangements need to be in place to allow decisions to be made on the implementation of predetermined, urgent protective actions for the public, based on predefined plant conditions.**
— **Arrangements need to be in place to enable urgent protective actions to be extended or modified in response to developing plant conditions or monitoring results. Arrangements are also needed to enable early protective actions to be initiated on the basis of monitoring results.**
— **Arrangements need to be in place to ensure that protective actions and other response actions in a nuclear emergency do more good than harm. A comprehensive approach to decision making needs to be in place to ensure that this balance is achieved.**

— **Arrangements need to be in place to assist decision makers, the public and others (e.g. medical staff) to gain an understanding of radiological health hazards in a nuclear emergency in order to make informed decisions on protective actions. Arrangements also need to be in place to address public concerns locally, nationally and internationally.**

Transition from the emergency phase to the recovery phase and analysis of the response

Specific policies, guidelines, criteria and arrangements for the transition from the emergency phase to the recovery phase were not developed until after the Fukushima Daiichi accident. In developing these arrangements, the Japanese authorities applied the latest recommendations of the International Commission on Radiological Protection (ICRP).

Analyses of the accident and of the emergency response were performed and presented in the form of reports, including those issued by the Government of Japan, the operating organization (TEPCO), and two investigation committees created by the Government and the Parliament, respectively.

After the accident, national emergency preparedness and response arrangements in Japan were, in many cases, revised to take account of the findings of these analyses and of relevant IAEA safety standards in the area of emergency preparedness and response.

— **Arrangements need to be developed at the preparedness stage for termination of protective actions and other response actions, and for transition to the recovery phase.**
— **Timely analysis of an emergency and the response to it, drawing lessons and identifying possible improvements, enhances emergency arrangements.**

Response within the international framework for emergency preparedness and response

An extensive international framework for emergency preparedness and response was in place at the time of the accident, comprising international legal instruments, IAEA safety standards and operational arrangements.[7]

At the time of the accident, the IAEA had four roles in the response to a nuclear or radiological emergency: (1) notification and exchange of official information through officially designated contact points; (2) provision of timely, clear and understandable information; (3) provision and facilitation of international assistance on request; and (4) coordination of the inter-agency response.

The international response to the accident involved many States and a number of international organizations.

The IAEA liaised with the official contact point in Japan, shared information on the emergency as it developed, and kept States, relevant international organizations and the public informed. Communication with the official contact point in Japan in the early phase of the emergency response was difficult. The IAEA Director General's visit to Japan, and the subsequent deployment of liaison officers to Tokyo, improved communication between the IAEA and the contact point. The IAEA also sent expert missions to Japan and coordinated the inter-agency response.

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[7] The primary international legal instruments are the Convention on Early Notification of a Nuclear Accident and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency. The international safety standards in the area of emergency preparedness and response at the time of the accident were IAEA Safety Standards Series No. GS-R-2 and No. GS-G-2.1. Safety Series No. 115 also included elements related to emergency preparedness and response. The international operational arrangements comprised the Emergency Notification and Assistance Technical Operations Manual (ENATOM), IAEA Response and Assistance Network (RANET) and Joint Radiation Emergency Management Plan of the International Organizations (JPLAN).

Different States[8] either took or recommended different protective actions for their nationals in Japan in response to the accident. These differences were generally not well explained to the public and occasionally caused confusion and concern.

Relevant organizations participating in the Inter-Agency Committee on Radiological and Nuclear Emergencies regularly exchanged information. Joint press releases were also issued.

— **The implementation of international arrangements for notification and assistance needs to be strengthened.**
— **There is a need to improve consultation and sharing of information among States on protective actions and other response actions.**

RADIOLOGICAL CONSEQUENCES

Radioactivity in the environment

The accident resulted in the release of radionuclides to the environment. Assessments of the releases have been performed by many organizations using different models. Most of the atmospheric releases were blown eastward by the prevailing winds, depositing onto and dispersing within the North Pacific Ocean. Uncertainties in estimations of the amount and composition of the radioactive substances were difficult to resolve for reasons that included the lack of monitored data on the deposition of the atmospheric releases on the ocean.

Changes in the wind direction meant that a relatively small part of the atmospheric releases were deposited on land, mostly in a north-westerly direction from the Fukushima Daiichi nuclear power plant. The presence and activity of radionuclides deposited in the terrestrial environment were monitored and characterized. The measured activity of radionuclides decreases over time due to physical decay, environmental transport processes and cleanup activities.

In addition to radionuclides entering the ocean from the atmospheric deposition, there were liquid releases and discharges from the Fukushima Daiichi nuclear power plant directly into the sea at the site. The precise movement of radionuclides in the ocean is difficult to assess by measurements alone, but a number of oceanic transport models have been used to estimate the oceanic dispersion.

Radionuclides such as iodine-131, caesium-134 and caesium-137 were released and found in drinking water, food and some non-edible items. Restrictions to prevent the consumption of these products were established by the Japanese authorities in response to the accident.

— **In case of an accidental release of radioactive substances to the environment, the prompt quantification and characterization of the amount and composition of the release is needed. For significant releases, a comprehensive and coordinated programme of long term environmental monitoring is necessary to determine the nature and extent of the radiological impact on the environment at the local, regional and global levels.**

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[8] The primary responsibility for emergency preparedness and response for a nuclear or radiological emergency rests with the State, as does the primary responsibility for the protection of human life, health, property and the environment.

Protecting people against radiation exposure

Following the accident, the Japanese authorities applied conservative reference levels of dose included in the recent ICRP recommendations[9]. The application of some of the protective measures and actions proved to be difficult for the implementing authorities and very demanding for the people affected.

There were some differences between the national and international criteria and guidance for controlling drinking water, food and non-edible consumer products in the longer term aftermath of the accident, once the emergency phase had passed.

— **Relevant international bodies need to develop explanations of the principles and criteria for radiation protection that are understandable for non-specialists in order to make their application clearer for decision makers and the public. As some protracted protection measures were disruptive for the affected people, a better communication strategy is needed to convey the justification for such measures and actions to all stakeholders, including the public.**
— **Conservative decisions related to specific activity and activity concentrations in consumer products and deposition activity led to extended restrictions and associated difficulties. In a prolonged exposure situation, consistency among international standards, and between international and national standards, is beneficial, particularly those associated with drinking water, food, non-edible consumer products and deposition activity on land.**

Radiation exposure

In the short term, the most significant contributors to the exposure of the public were: (1) external exposure from radionuclides in the plume and deposited on the ground; and (2) internal exposure of the thyroid gland, due to the intake of iodine-131, and internal exposure of other organs and tissues, mainly due to the intake of caesium-134 and caesium-137. In the long term, the most important contributor to the exposure of the public will be external radiation from the deposited caesium-137.

The early assessments of radiation doses used environmental monitoring and dose estimation models, resulting in some overestimations. For the estimates in this report, personal monitoring data provided by the local authorities were also included to provide more robust information on the actual individual doses incurred and their distribution. These estimates indicate that the effective doses incurred by members of the public were low and generally comparable with the range of effective doses incurred due to global levels of natural background radiation.

In the aftermath of a nuclear accident involving releases of iodine-131 and its intake by children, the uptake and subsequent doses to their thyroid glands are a particular concern. Following the Fukushima Daiichi accident, the reported thyroid equivalent doses of children were low because their intake of iodine-131 was limited, partly due to restrictions placed on drinking water and food, including leafy vegetables and fresh milk. There are uncertainties concerning the iodine intakes

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[9] International recommendations on radiation protection are issued by the ICRP. These recommendations are taken into account in the establishment of international safety standards, including radiation protection standards (the International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources (the Basic Safety Standards, or BSS)), which were developed and established by several international organizations and issued under the aegis of the IAEA. The BSS are used worldwide in the development of national regulations for the protection of people and the environment from the potential detrimental effects of exposure to ionizing radiation. The 2007 ICRP recommendations provided a revised framework for radiation protection. These included introducing reference levels for protection strategies. At the time of the accident, the BSS were being revised, inter alia, to take account of these recommendations.

immediately following the accident due to the scarcity of reliable personal radiation monitoring data for this period.

By December 2011, around 23 000 emergency workers had been involved in the emergency operations. The effective doses incurred by most of them were below the occupational dose limits in Japan. Of this number, 174 exceeded the original criterion for emergency workers and 6 emergency workers exceeded the temporarily revised effective dose criterion in an emergency established by the Japanese authority. Some shortcomings occurred in the implementation of occupational radiation protection requirements, including during the early monitoring and recording of radiation doses of emergency workers, in the availability and use of some protective equipment and in associated training.

— **Personal radiation monitoring of representative groups of members of the public provides invaluable information for reliable estimates of radiation doses and needs to be used together with environmental measurements and appropriate dose estimation models for assessing public dose.**
— **While dairy products were not the main pathway for the ingestion of radioiodine in Japan, it is clear that the most important method of limiting thyroid doses, especially to children, is to restrict the consumption of fresh milk from grazing cows.**
— **A robust system is necessary for monitoring and recording occupational radiation doses, via all relevant pathways, particularly those due to internal exposure that may be incurred by workers during severe accident management activities. It is essential that suitable and sufficient personal protective equipment be available for limiting the exposure of workers during emergency response activities and that workers be sufficiently trained in its use.**

Health effects

No early radiation induced health effects were observed among workers or members of the public that could be attributed to the accident.

The latency time for late radiation health effects can be decades, and therefore it is not possible to discount the potential occurrence of such effects among an exposed population by observations a few years after exposure. However, given the low levels of doses reported among members of the public, the conclusions of this report are in agreement with those of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) to the United Nations General Assembly.[10] UNSCEAR found that "no discernible increased incidence of radiation-related health effects are expected among exposed members of the public and their descendants" (which was reported within the context of the health implications related to "levels and effects of radiation exposure due to the nuclear accident after the 2011 great east-Japan earthquake and tsunami").[11] Among the group of workers who received effective doses of 100 mSv or more, UNSCEAR concluded that "an increased risk of cancer would be expected in the future. However, any increased incidence of cancer in this group is expected to be indiscernible because of the difficulty of confirming such a small incidence against the normal statistical fluctuations in cancer incidence."[12]

The Fukushima Health Management Survey was implemented to monitor the health of the affected population of Fukushima Prefecture. This survey is aimed at the early detection and treatment of

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[10] UNITED NATIONS, Report of the United Nations Scientific Committee on the Effects of Atomic Radiation, A/68/46, UN, New York (2013).

[11] The World Health Organization (WHO) also published a health risk assessment in 2013 on the basis of preliminary estimated doses. The results are presented in this report.

[12] See footnote 10.

diseases, as well as prevention of lifestyle related diseases. At the time of writing, an intensive screening of children's thyroid glands is taking place as part of the survey. Highly sensitive equipment is being used, which has detected asymptomatic thyroid abnormalities among a significant number of surveyed children (which would not have been detectable by clinical means). The abnormalities identified in the survey are unlikely to be associated with radiation exposure from the accident and most probably denote the natural occurrence of thyroid abnormalities in children of this age. The incidence of thyroid cancer in children is the most likely health effect after an accident involving significant releases of radioiodine. Because the reported thyroid doses attributable to the accident were generally low, an increase in childhood thyroid cancer attributable to the accident is unlikely. However, uncertainties remained concerning the thyroid equivalent doses incurred by children immediately after the accident.

Prenatal radiation effects have not been observed and are not expected to occur, given that the reported doses are well below the threshold at which these effects may take place. Unwanted terminations of pregnancy attributable to the radiological situation have not been reported. Concerning the possibility of parents' exposures resulting in hereditary effects in their descendants, UNSCEAR concluded that, in general, "although demonstrated in animal studies, an increase in the incidence of hereditary effects in human populations cannot at present be attributed to radiation exposure".[13]

Some psychological conditions were reported among the population affected by the nuclear accident. Since a number of these people had suffered the combined impacts of a major earthquake and a devastating tsunami as well as the accident, it is difficult to assess to what extent these effects could be attributed to the nuclear accident alone. The Fukushima Health Management Survey's Mental Health and Lifestyle Survey shows associated psychological problems in some vulnerable groups of the affected population, such as increases in anxiety and post-traumatic stress disorders. UNSCEAR estimated that "The most important health effect [from the accident] is on mental and social well-being, related to the enormous impact of the earthquake, tsunami and nuclear accident, and the fear and stigma related to the perceived risk of exposure to ionizing radiation."[14]

— **The risks of radiation exposure and the attribution of health effects to radiation need to be clearly presented to stakeholders, making it unambiguous that any increases in the occurrence of health effects in populations are not attributable to exposure to radiation if levels of exposure are similar to the global average background levels of radiation.**
— **After a nuclear accident, health surveys are very important and useful, but should not be interpreted as epidemiological studies. The results of such health surveys are intended to provide information to support medical assistance to the affected population.**
— **There is a need for radiological protection guidance to address the psychological consequences to members of the affected populations in the aftermath of radiological accidents. A Task Group of the ICRP has recommended that "strategies for mitigating the serious psychological consequences arising from radiological accidents be sought".[15]**

[13] UNITED NATIONS, Report of the United Nations Scientific Committee on the Effects of Atomic Radiation, A/67/46, UN, New York (2012).

[14] UNITED NATIONS, Sources, Effects and Risks of Ionizing Radiation, UNSCEAR 2013 Report, Vol. I, Scientific Annex A: Levels and Effects of Radiation Exposure Due to the Nuclear Accident after the 2011 Great East-Japan Earthquake and Tsunami, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2014).

[15] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Report of ICRP Task Group 84 on Initial Lessons Learned from the Nuclear Power Plant Accident in Japan vis-à-vis the ICRP System of Radiological Protection, ICRP, Ottawa (2012).

— **Factual information on radiation effects needs to be communicated in an understandable and timely manner to individuals in affected areas in order to enhance their understanding of protection strategies, to alleviate their concerns and support their own protection initiatives.**

Radiological consequences for non-human biota

No observations of direct radiation induced effects in plants and animals have been reported, although limited observational studies were conducted in the period immediately after the accident. There are limitations in the available methodologies for assessing radiological consequences, but, based on previous experience and the levels of radionuclides present in the environment, it is unlikely that there would be any major radiological consequences for biota populations or ecosystems as a consequence of the accident.

— **During any emergency phase, the focus has to be on protecting people. Doses to the biota cannot be controlled and could be potentially significant on an individual basis. Knowledge of the impacts of radiation exposure on non-human biota needs to be strengthened by improving the assessment methodology and understanding of radiation induced effects on biota populations and ecosystems. Following a large release of radionuclides to the environment, an integrated perspective needs to be adopted to ensure sustainability of agriculture, forestry, fishery and tourism, and of the use of natural resources.**

POST-ACCIDENT RECOVERY

Off-site remediation of areas affected by the accident

The long term goal of post-accident recovery[16] is to re-establish an acceptable basis for a fully functioning society in the affected areas. Consideration needs to be given to remediation[17] of the areas affected by the accident in order to reduce radiation doses, consistent with adopted reference levels. In preparing for the return of evacuees, factors such as the restoration of infrastructure and the viability and sustainable economic activity of the community need to be considered.

Prior to the Fukushima Daiichi accident, policies and strategies for post-accident remediation were not in place in Japan, and it became necessary to develop them in the period after the accident. The remediation policy was enacted by the Government of Japan in August 2011.[18] It assigned responsibilities to the national and local governments, the operator and the public, and created the necessary institutional arrangements for the implementation of a coordinated work programme.

A remediation strategy was developed and implementation began. The strategy specifies that priority areas for remediation are residential areas, including buildings and gardens, farmland, roads and infrastructure, with emphasis on the reduction of external exposures.

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[16] Post-accident recovery includes: the remediation of areas affected by the accident; the stabilization of damaged on-site facilities and preparations for decommissioning; the management of contaminated material and radioactive waste arising from these activities; and community revitalization and stakeholder engagement.

[17] Remediation is defined as any measures that may be carried out to reduce the radiation exposure from existing contamination of land areas through actions applied to the contamination itself (the source) or to the exposure pathways to humans.

[18] Act on Special Measures Concerning the Handling of Environmental Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District — Off the Pacific Ocean Earthquake that Occurred on March 11, 2011, Act No. 110, 2011.

External dose from radionuclides deposited on the ground and other surfaces is the main pathway of exposure. The remediation strategy is therefore focused on decontamination activities to reduce the levels of radiocaesium present in priority areas, thereby reducing the potential for such exposures. Internal doses continue to be controlled by restrictions on food, as well as through remediation activities on agricultural land.

Following the accident, the authorities in Japan adopted a ‘reference level’ as a target level of dose for the overall remediation strategy. This level was consistent with the lower end of the range specified in international guidance. The application of a low reference level has the effect of increasing the quantity of contaminated materials generated in remediation activities, and thereby increasing the costs and the demands on limited resources. The experience obtained in Japan could be used in developing practical guidance on the application of international safety standards in post-accident recovery situations.

Two categories of contaminated areas were defined on the basis of additional annual doses estimated in the autumn of 2011. The national Government was assigned responsibility for formulating and implementing remediation plans in the first area (the ‘Special Decontamination Area’) — within a radius of 20 km of the Fukushima Daiichi site and in areas where additional annual doses arising from contamination on the ground were projected to exceed 20 mSv in the first year after the accident. The municipalities were given responsibility for implementing remediation activities in the other area (the ‘Intensive Contamination Survey Area’), where the additional annual doses were projected to exceed 1 mSv but to remain below 20 mSv. Specific dose reduction goals were set, including a long term goal of achieving an additional annual dose of 1 mSv or less.

— **Pre-accident planning for post-accident recovery is necessary to improve decision making under pressure in the immediate post-accident situation. National strategies and measures for post-accident recovery need to be prepared in advance in order to enable an effective and appropriate overall recovery programme to be put in place in case of a nuclear accident. These strategies and measures need to include the establishment of a legal and regulatory framework; generic remediation strategies and criteria for residual radiation doses and contamination levels; a plan for stabilization and decommissioning of damaged nuclear facilities; and a generic strategy for managing large quantities of contaminated material and radioactive waste.**
— **Remediation strategies need to take account of the effectiveness and feasibility of individual measures and the amount of contaminated material that will be generated in the remediation process.**
— **As part of the remediation strategy, the implementation of rigorous testing and controls on food is necessary to prevent or minimize ingestion doses.**
— **Further international guidance is needed on the practical application of safety standards for radiation protection in post-accident recovery situations.**

On-site stabilization and preparations for decommissioning

A comprehensive, high level strategic plan for stabilization and decommissioning of the damaged nuclear power plant was developed jointly by TEPCO and the relevant Japanese Government agencies. The plan was first issued in December 2011 and subsequently revised to reflect the experience gained and an improved understanding of the conditions of the damaged nuclear power plant, as well as the magnitude of the future challenges. The strategic plan addresses the complex nature of on-site work and includes: the approach to ensure safety; measures towards decommissioning; systems and environments to facilitate the work; and research and development requirements.

At the time of writing, safety functions had been re-established and structures, systems and components were in place to reliably maintain stable conditions. However, there was a continuing need for control of ingress of groundwater to the damaged and contaminated reactor buildings. The resulting contaminated water was being treated to remove radionuclides to the extent possible and was stored in more than 800 tanks. More sustainable solutions are needed, considering all options, including the possible resumption of controlled discharge to the sea. Final decision making will require engaging relevant stakeholders and consideration of socioeconomic conditions in the consultation process, as well as implementation of a comprehensive monitoring programme.

Plans for the management of spent fuel and fuel debris were developed and removal of fuel from spent fuel pools began.[19] A conceptual model of future activities for removing fuel debris was developed, which takes account of the many preliminary steps required, including visual confirmation of the configuration and composition of the debris. The high radiation dose levels in the damaged reactors meant that no such confirmation had been possible at the time of writing.

Japanese authorities have estimated that the timescale for completing decommissioning activities is likely to be in the range of 30–40 years. Decisions regarding the final conditions of the plant and site will be the subject of further analysis and discussions.

- **Following an accident, a strategic plan for maintaining long term stable conditions and for the decommissioning of accident damaged facilities is essential for on-site recovery. The plan needs to be flexible and readily adaptable to changing conditions and new information.**
- **Retrieving damaged fuel and characterizing and removing fuel debris necessitate solutions that are specific to the accident, and special methods and tools may need to be developed.**

Management of contaminated material and radioactive waste

Stabilization of a damaged nuclear power plant and the on-site decontamination and remediation efforts in the surrounding areas result in large quantities of contaminated material and radioactive waste. On the site, large amounts of contaminated solid and liquid material, as well as radioactive waste, have been generated following various recovery activities.[20] The management of such material — with its varying physical, chemical and radiological properties — is complex and requires significant efforts.

Following the Fukushima Daiichi accident, there were difficulties in establishing locations to store the large amounts of contaminated material arising from off-site remediation activities. At the time of writing, several hundred temporary storage facilities had been established in local communities and efforts to establish an interim storage facility were continuing.

- **National strategies and measures for post-accident recovery need to include the development of a generic strategy for managing contaminated liquid and solid material and radioactive waste, supported by generic safety assessments for discharge, storage and disposal.**

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[19] Removal of fuel from the Unit 4 spent fuel pool was completed in December 2014.

[20] The distinction between contaminated material and radioactive waste depends upon the radionuclides and the activity concentrations associated with the materials.

Community revitalization and stakeholder engagement

The nuclear accident and radiation protection measures introduced in both the emergency and post-accident recovery phases have had significant consequences for the way of life of the affected population. Evacuation and relocation measures and restrictions on food involved hardships for the people affected. The revitalization and reconstruction projects introduced in Fukushima Prefecture were developed from an understanding of the socioeconomic consequences of the accident. These projects address issues such as reconstruction of infrastructure, community revitalization and support and compensation.

Communication with the public on recovery activities is essential to build trust. To communicate effectively, it is necessary for experts to understand the information needs of the affected population and to provide understandable information through relevant means. Communication improved in the aftermath of the accident, and the affected population became increasingly involved in decision making and remediation measures.

— **It is necessary to recognize the socioeconomic consequences of any nuclear accident and of the subsequent protective actions, and to develop revitalization and reconstruction projects that address issues such as reconstruction of infrastructure, community revitalization and compensation.**
— **Support by stakeholders is essential for all aspects of post-accident recovery. In particular, engagement of the affected population in the decision making processes is necessary for the success, acceptability and effectiveness of the recovery and for the revitalization of communities. An effective recovery programme requires the trust and the involvement of the affected population. Confidence in the implementation of recovery measures has to be built through processes of dialogue, the provision of consistent, clear and timely information, and support to the affected population.**

THE FUKUSHIMA DAIICHI ACCIDENT

SUMMARY REPORT

1. INTRODUCTION

The Great East Japan Earthquake occurred on 11 March 2011. It was caused by a sudden release of energy at the interface where the Pacific tectonic plate forces its way under the North American tectonic plate. A section of the Earth's crust, estimated to be about 500 km in length and 200 km wide, was ruptured, causing a massive earthquake with a magnitude of 9.0 and a tsunami which struck a wide area of coastal Japan, including the north-eastern coast, where several waves reached heights of more than ten metres. The earthquake and tsunami caused great loss of life and widespread devastation in Japan. More than 15 000 people were killed and over 6000 injured and, at the time of writing of this report[21], around 2500 people were still reported to be missing [1]. Considerable damage was caused to buildings and infrastructure, particularly along Japan's north-eastern coast.

At the Fukushima Daiichi nuclear power plant (NPP), operated by the Tokyo Electric Power Company (TEPCO), the earthquake caused damage to the electric power supply lines to the site, and the tsunami caused substantial destruction of the operational and safety infrastructure on the site. The combined effect led to the loss of off-site and on-site electrical power. This resulted in the loss of the cooling function at the three operating reactor units[22] as well as at the spent fuel pools. The four other NPPs[23] along the coast were also affected to different degrees by the earthquake and tsunami. However, all operating reactor units at these plants were safely shut down.

Despite the efforts of the operators at the Fukushima Daiichi NPP to maintain control, the reactor cores in Units 1–3 overheated, the nuclear fuel melted, and the three containment vessels were breached. Hydrogen was released from the reactor pressure vessels, leading to explosions inside the reactor buildings in Units 1, 3 and 4 that damaged structures and equipment and injured personnel. Radionuclides were released from the plant to the atmosphere and were deposited on land and on the ocean. There were also direct releases into the sea.

People within a radius of 20 km of the site and in other designated areas were evacuated, and those within a radius of 20–30 km were instructed to shelter before later being advised to voluntarily evacuate. Restrictions were placed on the distribution and consumption of food and the consumption of drinking water. At the time of writing, many people were still living outside the areas from which they were evacuated.

Following stabilization of the conditions of the reactors at the Fukushima Daiichi NPP[24], work began to prepare for their eventual decommissioning. Efforts towards the recovery of the areas affected by the accident, including remediation and the revitalization of communities and infrastructure, began in 2011.

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[21] March 2015. In some cases, information was available up to June 2015 and has been included, where possible.

[22] Of the six units of the Fukushima Daiichi NPP, Units 1, 2 and 3 were operating at the time of the accident; Units 4, 5 and 6 were in planned shutdown.

[23] The Higashidori, Onagawa, Fukushima Daini and Tokai Daini NPPs.

[24] On 16 December 2011, the Government–TEPCO Integrated Response Office announced that the conditions for a 'cold shutdown state' had been achieved in Units 1–3. The term 'cold shutdown state' was defined by the Government of Japan at the time specifically for the Fukushima Daiichi NPP. The definition differs from the terminology used by the IAEA and others.

1.1. THE REPORT ON THE FUKUSHIMA DAIICHI ACCIDENT

At the IAEA General Conference in September 2012, the Director General announced that the IAEA would prepare a report on the Fukushima Daiichi accident. He later stated that this report would be "an authoritative, factual and balanced assessment, addressing the causes and consequences of the accident, as well as lessons learned" [2].

The report on the Fukushima Daiichi accident is the result of an extensive international collaborative effort involving five working groups with about 180 experts from 42 Member States (with and without nuclear power programmes) and several international bodies. This ensured a broad representation of experience and knowledge. An International Technical Advisory Group provided advice on technical and scientific issues. A Core Group, comprising IAEA senior level management, was established to give direction and to facilitate the coordination and review of the report. Additional internal and external review mechanisms were also instituted, as illustrated in Fig. 1.1.

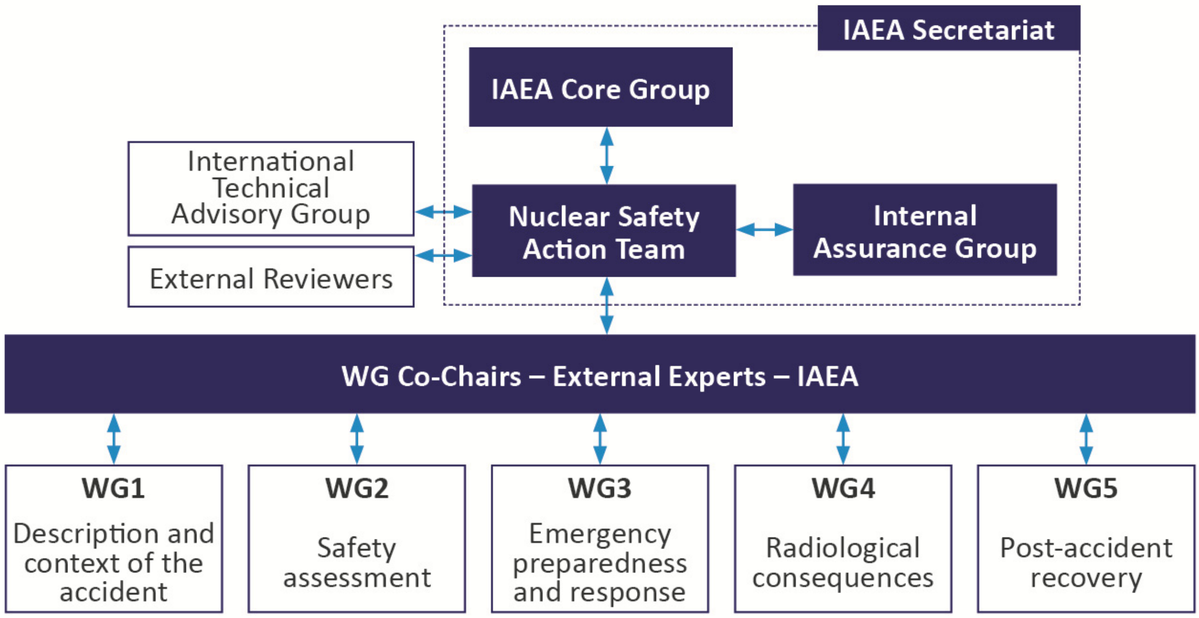


FIG. 1.1. IAEA organization structure for preparing the report on The Fukushima Daiichi Accident.

This Report by the Director General consists of an Executive Summary and a Summary Report. It draws on five detailed technical volumes prepared by international experts and on the contributions of the many experts and international bodies involved. The report provides a description of the accident and its causes, evolution and consequences, based on the evaluation of data and information from a large number of sources available up to March 2015, including the results of the work carried out in implementing the IAEA Action Plan on Nuclear Safety (the Action Plan)[25], and it highlights the main

[25] The Action Plan, unanimously endorsed by the 55th IAEA General Conference in 2011, defined a programme of work to strengthen the global nuclear safety framework. It consists of 12 main actions related to: safety assessments; IAEA peer reviews; emergency preparedness and response; national regulatory bodies; operating organizations; IAEA safety standards; the international legal framework; Member States planning to embark on a nuclear power programme; capacity building; protection of people and the environment from ionizing radiation; communication and information dissemination; and research and development. For a detailed discussion of the Action Plan, see Section 6.1.

observations and lessons. Significant amounts of data were provided by the Government of Japan and other organizations in Japan.

The five technical volumes are for a technical audience that includes the relevant authorities in IAEA Member States, international organizations, nuclear regulatory bodies, NPP operating organizations, designers of nuclear facilities and other experts in matters relating to nuclear power.

This Report by the Director General comprises the following six sections:

— Section 1: Introduction.
— Section 2: The accident and its causes, including a description of the sequence of events and an assessment of how extreme natural events led to the severe nuclear accident.
— Section 3: Emergency preparedness and response, including the arrangements for the protection of emergency workers and the public, and the implementation of these arrangements during and immediately after the accident.
— Section 4: The radiological consequences of the accident, including radiation exposure of workers and the public, and health and environmental effects.
— Section 5: Post-accident recovery activities, including decommissioning of the plant, remediation strategies for the off-site areas affected, waste management and strategies for revitalization.
— Section 6: An overview of the activities of the IAEA and the Contracting Parties to the Convention on Nuclear Safety in response to the accident.

Key observations and lessons arising from specific features of the accident are included in Sections 2–5. The relationship between the content of the Report by the Director General and the content of the technical volumes is illustrated in Fig. 1.2.

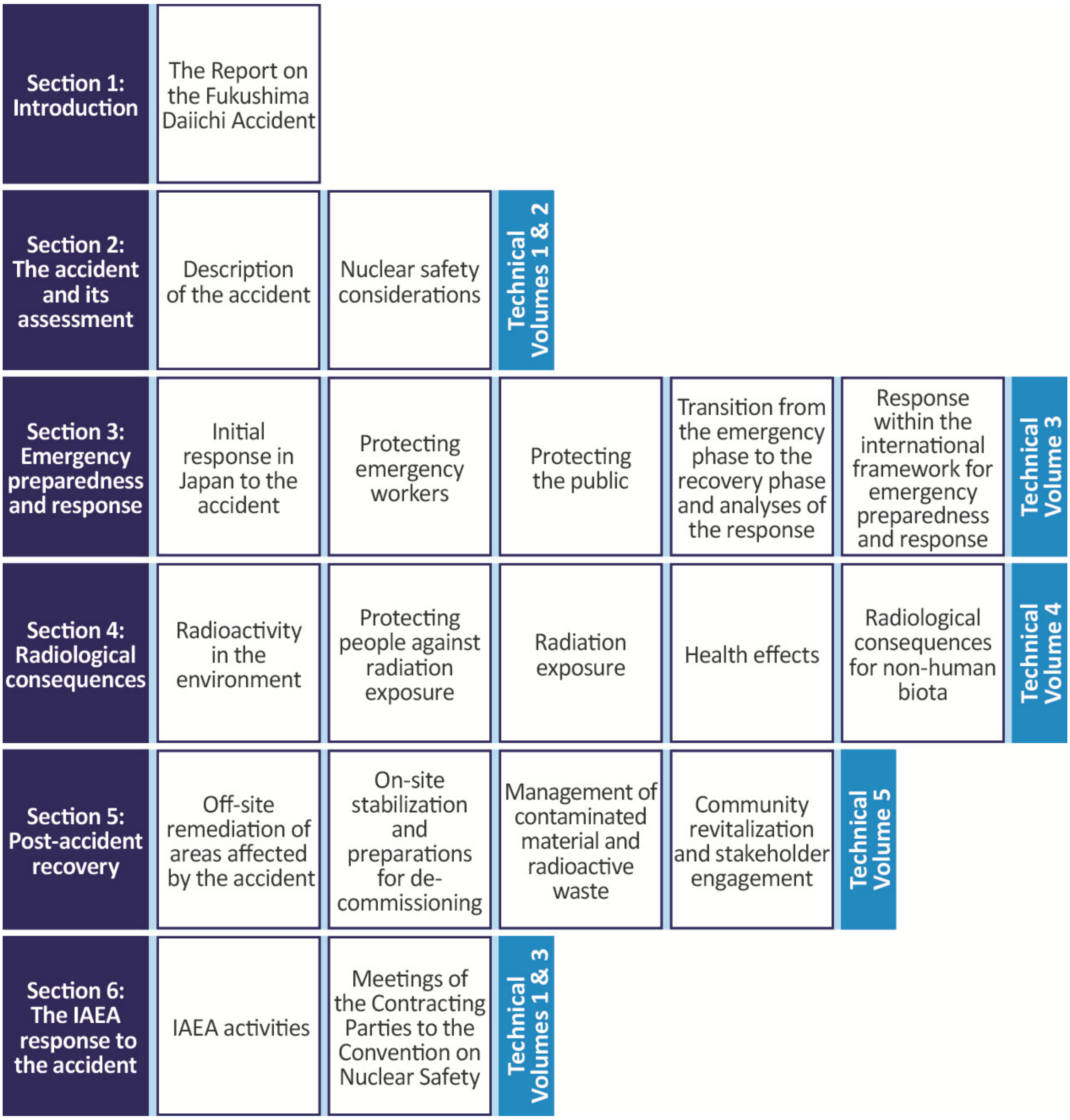


FIG. 1.2. Structure of the Summary Report and its relationship to the content of the technical volumes.

2. THE ACCIDENT AND ITS ASSESSMENT

This section provides a brief description of the accident at the Fukushima Daiichi NPP, followed by an assessment of factors that are considered to have contributed to its causes and consequences.

Section 2.1 describes the main events in chronological order, including the impact of the earthquake and tsunami and the subsequent events.

Section 2.2 assesses the causes of the accident. It begins with an evaluation of the vulnerability of the Fukushima Daiichi NPP to external hazards and deals with its design, the accident progression, the efforts of the operators to maintain fundamental safety functions and the actions taken by them. This section also considers the effectiveness of the regulatory framework in Japan as well as the impact of human and organizational considerations on nuclear safety.

2.1. DESCRIPTION OF THE ACCIDENT

The description that follows is mainly based on information provided by the Government of Japan to the IAEA [3, 4], reports of the investigation committees established by the Japanese Government [5, 6], the National Diet of Japan [7] and TEPCO [8], including updates and supplements by TEPCO [9, 10], the regulatory body [11] and the IAEA missions listed in Section 6. Other sources from which information has been taken are cited separately.

Events are presented in chronological order. Some of the main events occurred in parallel or had an impact on actions taken in other locations on-site.

2.1.1. Initiating event and response

The earthquake and the loss of off-site power

The Great East Japan Earthquake of 11 March 2011 occurred at 14:46 Japan Standard Time (JST), 05:46 UTC[26], off the eastern coast of Japan. It was caused by a sudden release of energy at the interface where the Pacific tectonic plate forces its way under the North American tectonic plate (Fig. 2.1). The main shock, with a magnitude of 9.0 [12], lasted for more than two minutes, with several significant pulses and aftershocks. This event was among the largest recorded earthquakes, most of which also occurred in areas along the Pacific tectonic plate: the earthquakes of 1960 and 2010 in Chile, with a magnitude of 9.5 and 8.8, respectively, and those in Alaska (1964) and Sumatra (2004), both with a magnitude of 9.2.

[26] Universal Time Coordinated, which is nine hours behind JST. Unless indicated, the report uses JST for all times.

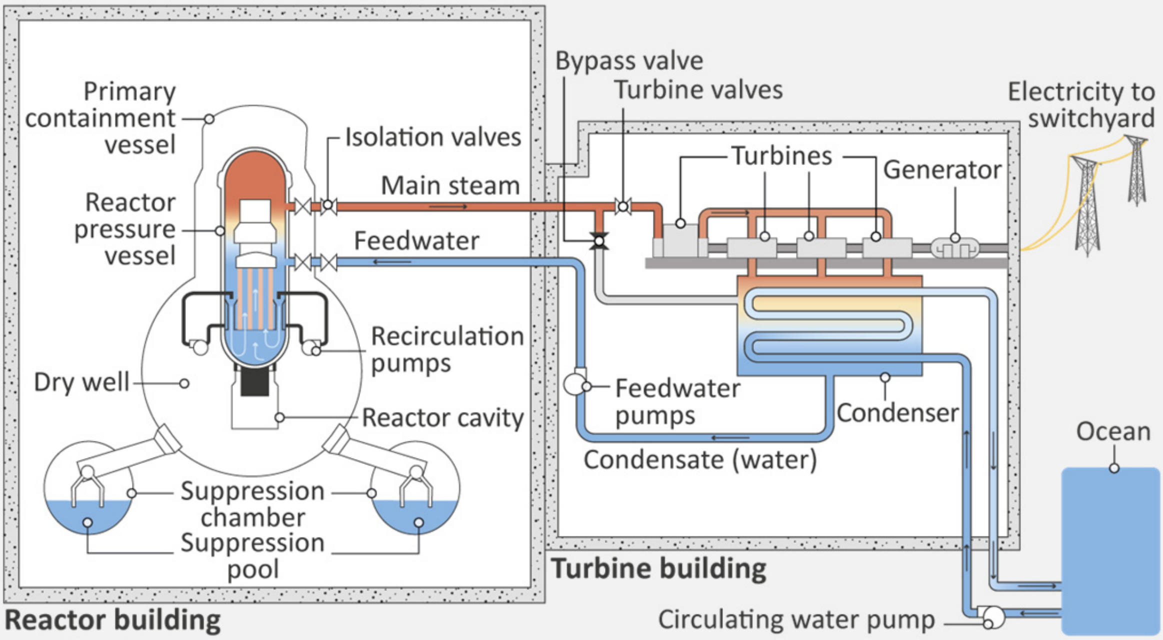
FIG. 2.1. The epicentre of the Great East Japan Earthquake and the NPPs nearby.

When the earthquake occurred, three of the six boiling water reactors (Box 2.1) at the Fukushima Daiichi NPP [13] were operating at full power and three were shut down for refuelling and maintenance. The operating reactors of Units 1–3 were shut down automatically when sensors at the plant detected the ground motion and triggered reactor protection systems in accordance with the design. This automatic action achieved control of reactivity.

When shut down, the reactor cores continued to generate heat (known as decay heat). To prevent the nuclear fuel from overheating, this heat had to be removed by cooling systems that were mainly run or controlled by electrical power. The earthquake caused damage to on-site switchyard equipment, off-site substation equipment, and the power lines supplying off-site AC power to the plant, leading to the loss of all off-site electrical power. The on-site replacement power facilities — emergency diesel generators — which were designed to deal with such loss of off-site power situations, automatically started in order to restore AC power in all six units.

Box 2.1. Boiling water reactors

Boiling water reactors use a closed, direct steam cycle loop, as shown schematically below. The working fluid is water that is used both as the coolant to remove heat and the moderator for controlling reactivity. Coolant water boils in the reactor core at a pressure of approximately 7 MPa, and the steam that is generated is used to drive turbines to generate electricity. After passing through the turbines, the steam is condensed back to water by being cooled by the condenser tubes that are filled with cold water taken from a heat sink, e.g. the ocean. The water resulting from condensation is then pumped back to the reactor as feedwater.



Units 1–3 were automatically isolated from their turbine systems due to the power interruption, resulting in increases in the temperature and pressure of the reactors due to the decay heat. The cooling of these reactors following isolation was accomplished by means of the following design and operational provisions (Box 2.2):

— In Unit 1, as the reactor pressure increased, both loops of the isolation condenser system started automatically and continued to cool the reactor. The operation of both isolation condenser loops lowered the reactor pressure and temperature so rapidly that the operators manually stopped them, in accordance with procedures, in order to prevent thermal stress on the reactor pressure vessel. Afterwards, only one of the loops was used by the operators to control the cooling rate[27] in a range prescribed by the procedures.

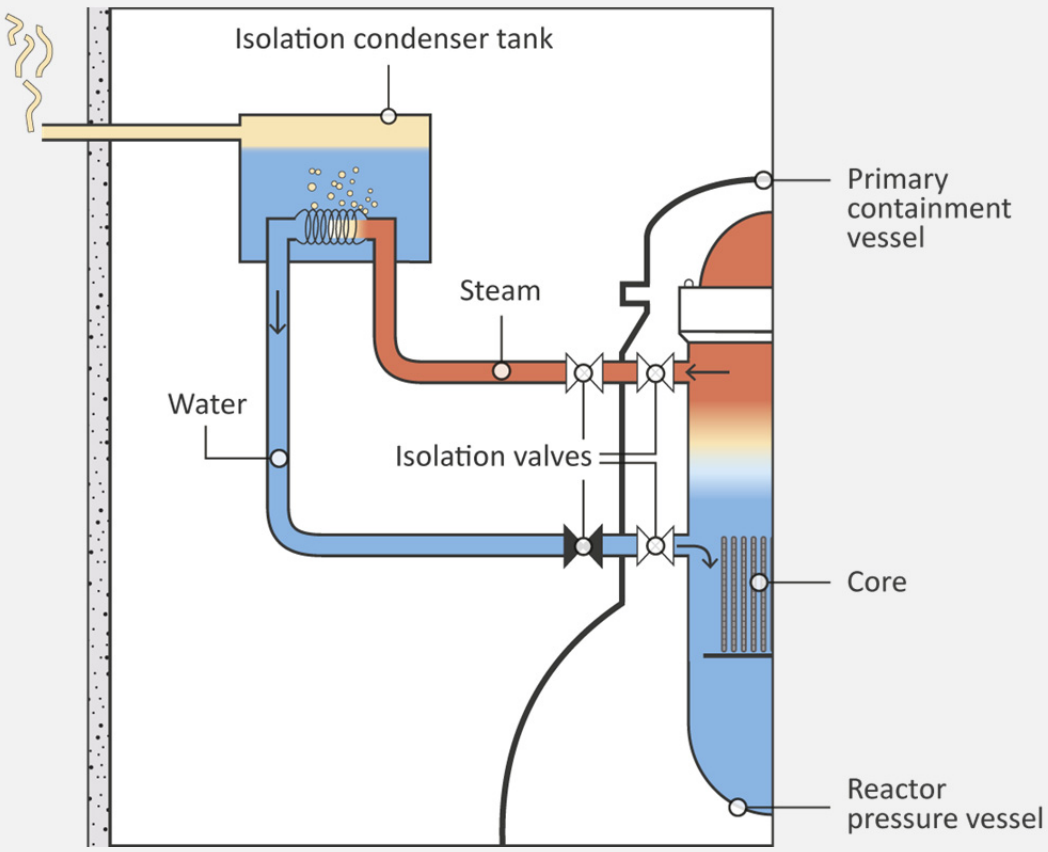
— In Units 2 and 3, the increase in reactor pressure automatically activated safety relief valves, which were designed to protect the reactor from overpressurization by releasing steam from the reactor vessel to the suppression pool section of the primary containment vessel. This resulted in a decrease in the reactor water levels. The operators manually activated the reactor core isolation cooling system in accordance with procedures.

[27] In boiling water reactors, the cooling rate is monitored and controlled by the reduction in reactor pressure, which, in turn, corresponds to the decrease in reactor temperature.

Box 2.2. Systems for cooling the core when the reactor is isolated from the turbines

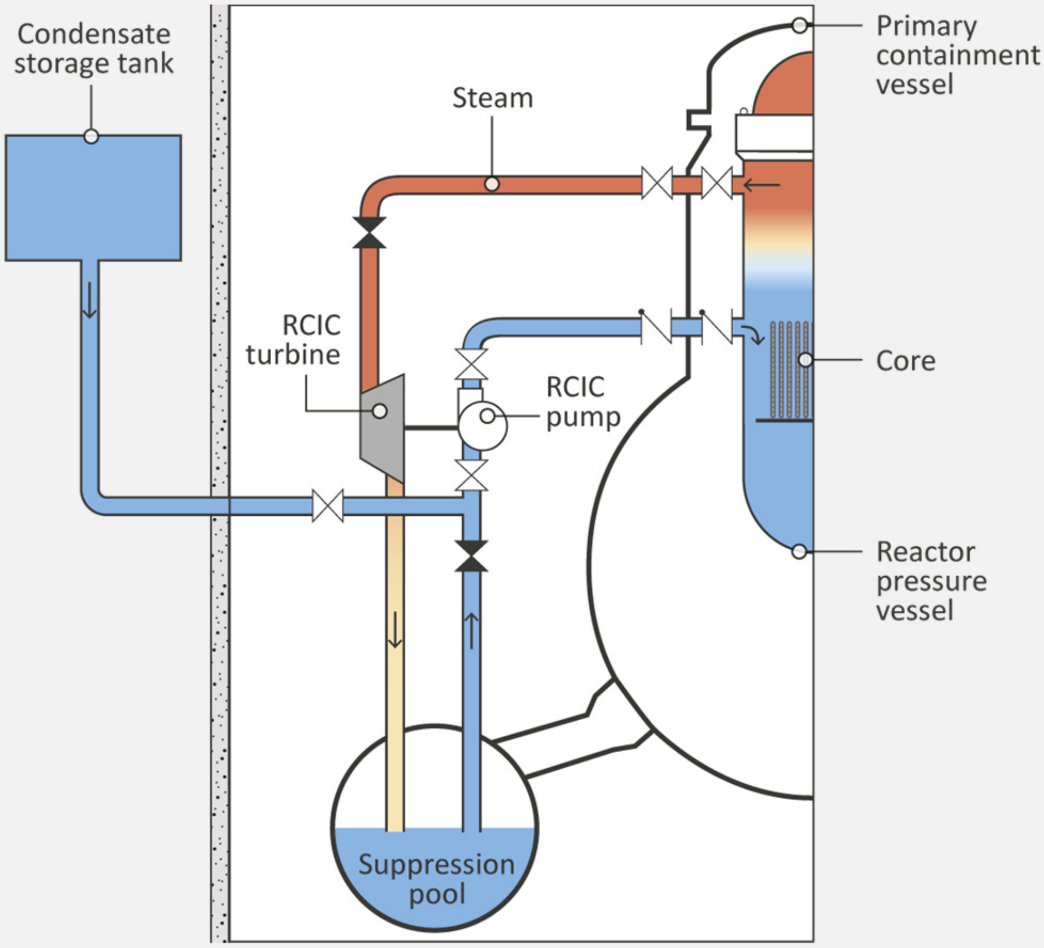
Normal shutdown cooling of boiling water reactors at high reactor pressure is accomplished by directing the steam from the reactor to the main condenser, bypassing the turbines (see Box 2.1). However, when the reactor is isolated, this path is not available and core cooling is provided by the systems designed for an isolated reactor under high pressure conditions which exist after reactor shutdown. In the design of the Fukushima Daiichi NPP, those were: the isolation condenser (IC) system for Unit 1 (the earlier design) and the reactor core isolation cooling (RCIC) system for Units 2–6.

Isolation condenser. In the Unit 1 design, there were two separate and redundant isolation condenser loops. In these closed loops, the primary side of the isolation condenser received steam generated in the reactor and condensed it by cooling inside the heat exchanger tubes that were submerged in colder water tanks (isolation condenser pools) located outside the primary containment vessel. Condensed steam was then sent as cold water back to the reactor by gravity (see the diagram below). Without mixing with the radioactive primary side water, the secondary side water in the isolation condenser pools boiled, and the evaporated steam was vented to the atmosphere, which served as the heat sink. The secondary side water volume of the isolation condenser (both trains together) was sufficient for eight hours of cooling before requiring replenishment from a dedicated water source.



Reactor core isolation cooling. In the design of Units 2–6, there were open cycle cooling systems that needed a source for adding water to the reactor system. In the reactor core isolation cooling systems, the steam from the reactor drove a small turbine which, in turn, ran a pump that injected water into the reactor at high pressure. The steam that ran the turbine was discharged and accumulated in the suppression pool section of the primary containment vessel, which served as the heat sink for absorbing waste heat. The water lost from the reactor was replenished by taking fresh water from the condensate storage tank (see the diagram below). When the tank emptied or the suppression pool became full, the water that accumulated in the suppression pool could be used, making the system essentially a closed loop cycle. The reactor core isolation cooling was designed to operate for at least four hours.

Box 2.2. Systems for cooling the core when the reactor is isolated from the turbines (cont.)



The decay heat from the nuclear fuel in Units 4–6 also had to be removed:

— In Unit 4, the equipment for cooling and refilling of spent fuel pool water[28] stopped working as a result of the loss of off-site power. The Unit 4 spent fuel pool, containing more than 1300 spent fuel assemblies, had the largest amount of decay heat to be removed among all the spent fuel pools of the units.
— In Unit 5, the reactor pressure, which was being kept elevated by the use of a pump for pressure testing purposes at the time of the earthquake, initially dropped when the pump stopped as a result of the loss of off-site power. The pressure started to rise due to decay heat, but unlike in Units 2 and 3, it remained well below the levels to activate the safety relief valves.
— In Unit 6, the reactor was near atmospheric pressure and room temperature with fuel in the core, and the decay heat was low.

[28] The spent fuel pools, which store the used and new fuel assemblies, are filled with water, providing radiation shielding and removal of heat from the nuclear fuel located there. However, without cooling, the pool water would heat up and eventually start evaporating. If this situation continues without refilling, the cooling of fuel stops when the water level falls and exposes the fuel. Overheating and exposure causes damage to the fuel and the release of radionuclides.

In the spent fuel pools of all units and the common spent fuel pool[29], which lost cooling and refilling capabilities upon the loss of off-site power, the temperatures of the pool water started to increase due to decay heat.

In response to the earthquake and the loss of off-site power, the operators activated the ‘event based’ abnormal operating procedures in all three main control rooms of the six units.[30] An earthquake emergency response team was activated at the on-site emergency response centre located within the seismically isolated building.[31] The Site Superintendent was responsible for directing the site response and for coordination with on-site and off-site organizations, as the head of TEPCO’s on-site emergency response centre. Three shift superintendents in each of the main control rooms were responsible for directing the actions in their units under the command of the Site Superintendent.

The units at the Fukushima Daiichi NPP responded to the initiating event — the earthquake and the concurrent loss of off-site power — as intended by the designers and as stipulated in the operating procedures (except for some operator actions that were restricted or delayed by the aftershocks) (Fig. 2.2).

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[29] As a shared auxiliary facility among the units, the common spent fuel pool, located in a separate building near Unit 4, stored over 6000 spent fuel assemblies, all of which needed to have their decay heat removed.

[30] Each pair of units shared a common main control room, i.e. Units 1 and 2, Units 3 and 4, and Units 5 and 6.

[31] The seismically isolated building was built as a result of experience gained from the effects of the Niigata-Chuetsu-Oki earthquake at the Kashiwazaki-Kariwa NPP in 2007, and was put into operation in July 2010. It was designed to withstand earthquakes and was equipped with backup power. Filtered ventilation and shielding were provided for protection from radioactivity.

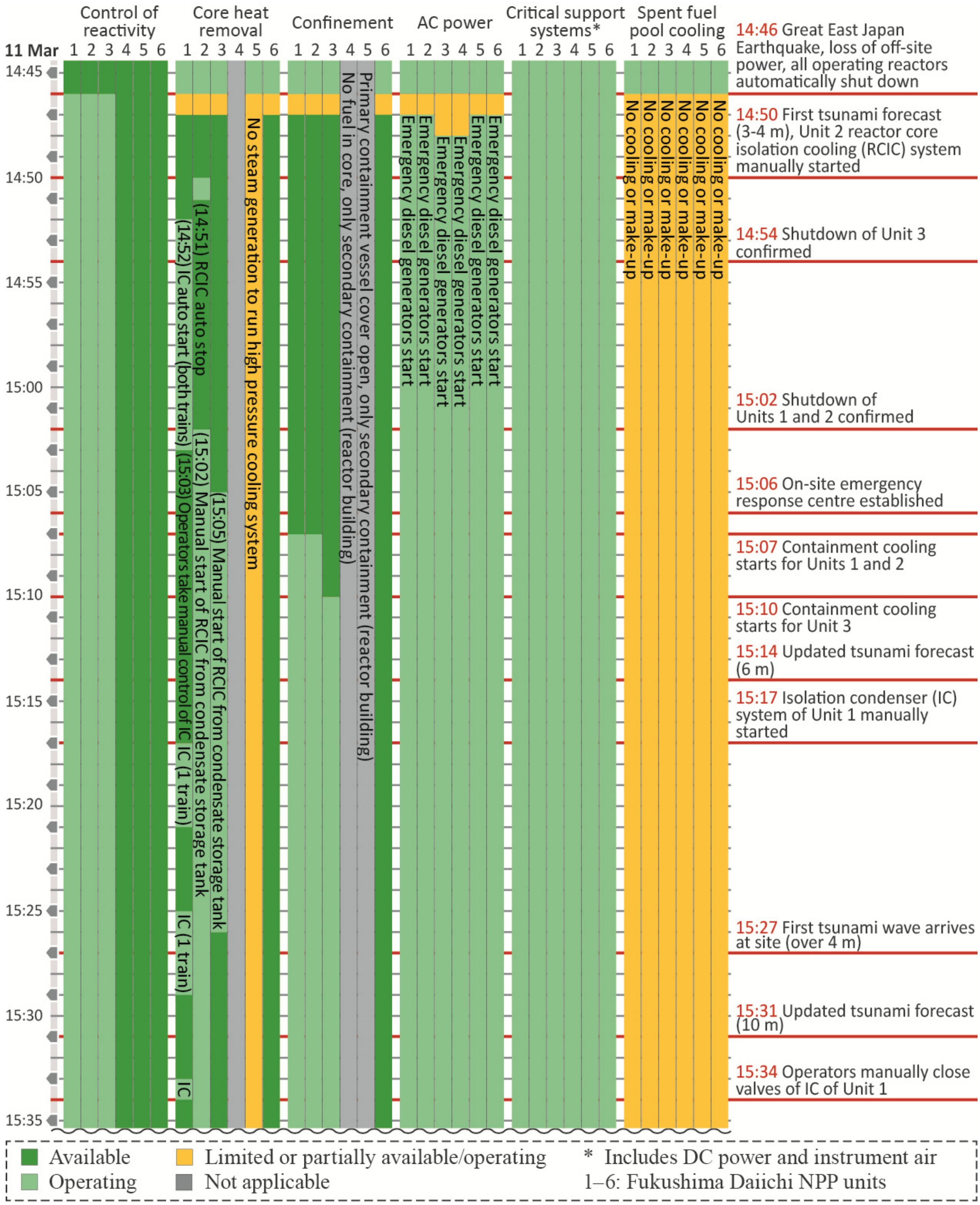

FIG. 2.2. Response of the Fukushima Daiichi NPP to the earthquake and the loss of off-site power.

The tsunami and the station blackout

In addition to causing the strong ground motion, the earthquake displaced a massive amount of water, giving rise to a series of large tsunami waves [14]. When these tsunami waves reached the coast, they had a devastating effect over a wide area (Fig. 2.3).

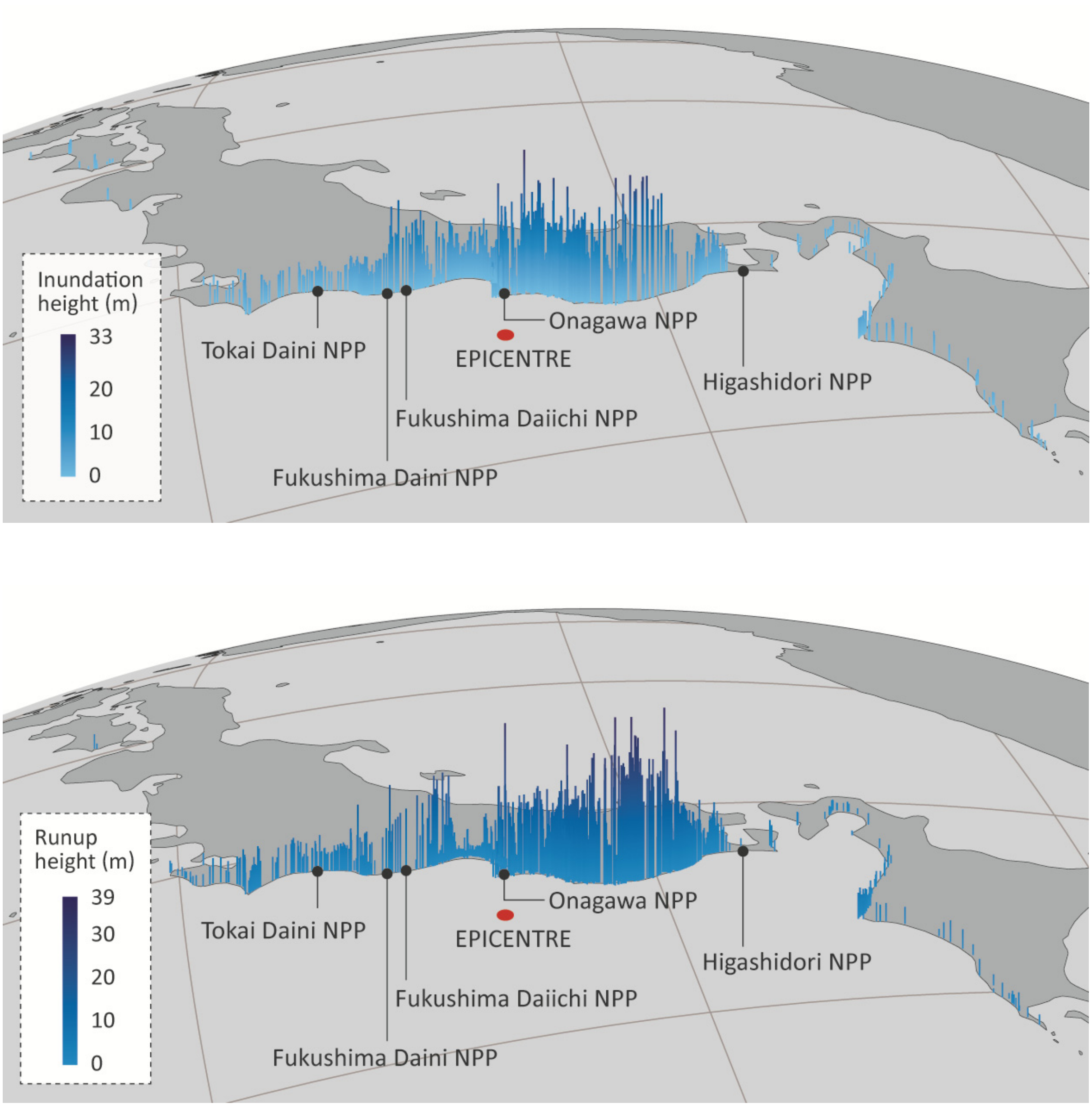

FIG. 2.3. The variation of tsunami wave impact, inundation (top) and runup (bottom)[32], based on the coastal geography and topography [15].

The tsunami waves started reaching the Fukushima Daiichi NPP about 40 minutes after the earthquake. The site was protected from the first wave, which had a 4–5 m runup height, by the

[32] Runup height is the height of the wave at the furthest inland point, and inundation height is the crest height of a wave compared to the sea level.

tsunami barrier seawalls that were designed to protect against a maximum tsunami height of 5.5 m [16]. However, about 10 minutes after the first wave, the second and largest wave, with a runup height of 14–15 m, overwhelmed the seawalls and inundated the site. It engulfed all structures and equipment located at the seafront, as well as the main buildings (including the reactor, turbine and service buildings) at higher elevations[33] (Fig. 2.4), causing the following sequence of events:

— The wave flooded and damaged the unhoused seawater pumps and motors at the seawater intake locations on the shoreline. This meant that essential plant systems and components, including the water cooled emergency diesel generators[34], could not be cooled to ensure their continuous operation.
— The wave flooded and damaged the dry cask storage building located near the seashore between Units 1–4 and Units 5–6. There were no significant impacts on the casks or the fuel stored in them, as was later confirmed [17].
— Water entered and flooded buildings, including all the reactor and turbine buildings, the common spent fuel storage building and diesel generator building. It damaged the buildings and the electrical and mechanical equipment inside at ground level and on the lower floors. The damaged equipment included the emergency diesel generators or their associated power connections, which resulted in the loss of emergency AC power. Only one of the air cooled emergency diesel generators — that of Unit 6 — was unaffected by the flooding[35]. It remained in operation, continuing to supply emergency AC power to the Unit 6 safety systems and allowing cooling of the reactor.

As a result of these events, Units 1–5 lost all AC power, a situation referred to as a station blackout.

Because of the station blackout in Units 1–5, the emergency operating procedures for 'loss of all AC power' [18] were initiated. A 'specific event', as defined in the regulations associated with the Act on Special Measures Concerning Nuclear Emergency Preparedness [19], hereinafter referred to as the Nuclear Emergency Act, based on the condition of 'some safety systems becoming unavailable', was declared by the Site Superintendent, who was the head of the on-site emergency response centre of the operating organization, TEPCO. Consequently, the relevant off-site agencies were informed in accordance with the requirements of the Nuclear Emergency Act.

The Fukushima Daiichi NPP units, similar to other plants of the same age, were designed to withstand a station blackout for eight hours, based on the capacity of the DC batteries in the reactor units[36].

[33] The administration buildings and the seismically isolated building that contained the on-site emergency response centre were on a cliff at an elevation of approximately 35 m (which was the original topographical site elevation before the site area was excavated for placing the units during construction).

[34] Each unit had a pair of emergency diesel generators, and Unit 6 had an additional generator. Of those 13 emergency diesel generators, Units 2, 4 and 6 each had one that was air cooled. Since they were air cooled, operability of these generators was not directly affected by the loss of cooling water caused by the damage to the seawater pumps.

[35] The air cooled emergency diesel generators of Units 2, 4 (located in ground floor of the common spent fuel building) and 6 (located on the first floor of a separate diesel generator building at higher elevation) appeared to be unaffected by the flooding. However, the components (i.e. switchgears, power centres, panels etc.) of the air cooled emergency diesel generators of Units 2 and 4, which were located in the basement of the common spent fuel building, suffered water damage.

[36] NPPs are generally equipped with on-site DC and additional backup AC power sources (i.e. gas turbine generators or diesel engines) to withstand a station blackout for a limited period of time, varying between 4 and 72 hours. The determination of the coping period is based mainly on the time that it would take to restore AC power sources to the NPP and the capacity of the available measures. During that time, equipment such as DC batteries, DC/AC inverters and other secondary backup AC sources (e.g. gas turbines or diesel generators) is used.

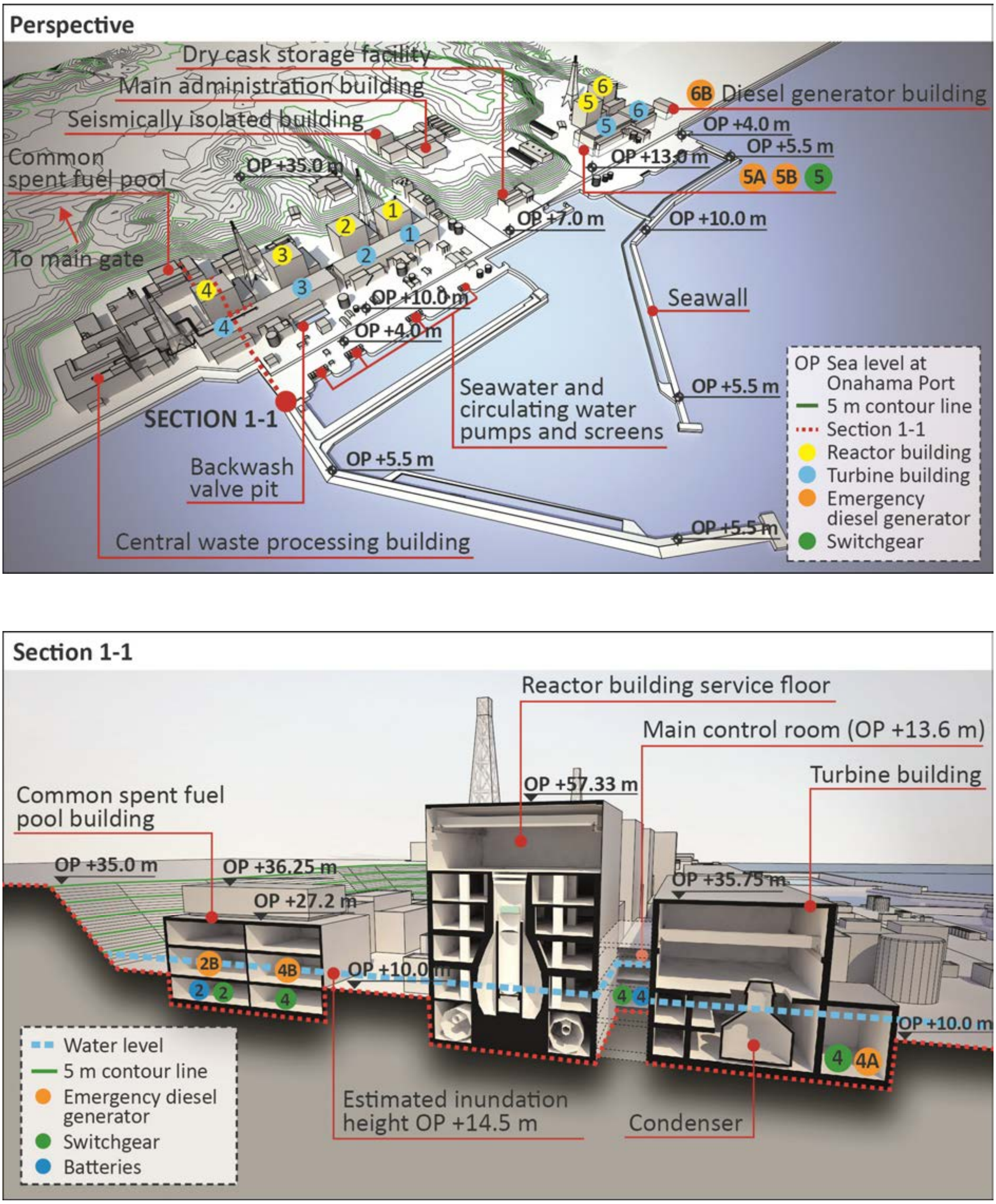

FIG. 2.4. The elevations and locations of structures and components at the Fukushima Daiichi NPP [20].

Loss of DC power in Units 1, 2 and 4

All units at the Fukushima Daiichi NPP were equipped with on-site DC sources as an emergency power supply, but the flooding also affected this equipment in Units 1, 2 and 4, inundating the DC batteries, power panels or connections. Consequently, DC power was gradually lost in Units 1, 2 and 4 during the first 10–15 minutes of the flooding, making it difficult to cope with the station blackout.

Due to the loss of all AC and DC power, the operators of Units 1 and 2 could no longer monitor essential plant parameters, such as reactor pressure and reactor water level, or the status of key systems and components used for core cooling. As mentioned earlier, the heat removal capability for the spent fuel pools in all units was already lost following the loss of off-site power. The additional loss of DC power in Units 1, 2 and 4 meant that operators could no longer monitor the water temperature and levels in the spent fuel pools of these units.

In the absence of procedures addressing the loss of all AC and DC power, the operators of Units 1, 2 and 4 did not have specific instructions on how to deal with a station blackout under these conditions. The operators and emergency response centre staff started reviewing available options and establishing possible ways to restore power and thereby regain the ability to monitor and control the plant.

Response in Units 3, 5 and 6

Units 3, 5 and 6 maintained power enabling the operators to observe the plant status as the main control room indications and controls were functioning. This allowed the operators to continue with their 'symptom based' emergency operating procedures in response to the events:

— In Unit 3, the safety relief valves automatically opened to protect the reactor vessel from overpressurization, and the operators manually restarted the reactor core isolation cooling system, controlling and monitoring the reactor water injection with the available DC power. They also shut off other non-critical equipment to maximize the availability of the DC batteries in order to extend the period of time for coping with the station blackout.
— DC power was also available in Unit 5. The reactor was not generating steam, so residual heat removal by a high pressure cooling system was not possible. Alternative options to depressurize the reactor vessel to enable coolant injection by low pressure systems were tried unsuccessfully, and the reactor vessel, which was pressurized and filled with water, continued to heat up and pressurize.
— Unit 6 did not experience a station blackout, since AC power was available from one operating emergency diesel generator. Here, the efforts focused on maintaining fundamental safety functions in response to the loss of off-site power. The reactor was at atmospheric pressure, making it possible to utilize the low pressure systems to inject cooling water; however, some of the necessary components of those systems were damaged by the flooding and required restoration.

2.1.2. Progression of the accident

The nuclear emergency in Units 1 and 2

As all electrical power was lost in Units 1 and 2, there were no indications available to the operators to determine whether the safety systems were operating properly, or operating at all, in order to maintain the fundamental safety functions[37]. Unable to determine the water level in the reactor and the operational status of the cooling systems, plant operators declared that the core cooling fundamental safety function was lost. Consequently, the on-site emergency response centre reported to the off-site organizations, TEPCO Headquarters and relevant government authorities, that nuclear emergency conditions for Units 1 and 2 existed on the basis of the 'inability of water injection of the emergency core cooling system', as defined in regulations [21].

[37] The fundamental safety function of reactivity control had been confirmed before the station blackout by indications showing that the control rods were inserted and the fission reaction had stopped.

Establishing the severe accident management strategy

The staff in the on-site emergency response centre started following the established severe accident management guidelines, and the operators in the common main control room of Units 1 and 2 activated the severe accident operating procedure. Since the core cooling appeared to be compromised, the accident management strategy focused on injecting water into the reactors in order to prevent, or mitigate, potential damage to the nuclear fuel. Two options for injecting water into the reactors were identified:

— The use of systems that could inject water directly into the reactors, even at high pressures, which required the restoration of AC power.
— The use of alternative equipment, such as mobile fire engines and the stationary diesel driven fire pump that could inject water at low pressures, which required depressurization of the reactors and alignment of the fire protection lines to inject water into the core.[38]

The on-site emergency response centre adopted a core cooling strategy that used the stationary diesel driven fire pump and the fire engines via the fire protection system to inject water into the reactors, in addition to connecting temporary power sources.

This accident strategy was given the highest priority for Units 1 and 2 and was applicable to all other units with some variations. For example, in Unit 5, the accident management action was to restore AC power using the available interconnecting line[39] to the operating emergency diesel generator in Unit 6.

Status of core cooling in Units 1 and 2

Just before the tsunami struck, the Unit 1 isolation condenser was stopped by the operators in accordance with established operating procedures to control the reactor cooling rate. This was accomplished by closing the valves (located outside the primary containment vessel and DC operated, as shown in Box 2.2). About 2.5 hours after the loss of indications, at 18:18 on 11 March, some of the status lamps for those valves were found to be functioning, confirming that the control valves were closed. The operators attempted to start the isolation condenser by opening those valves. However, the isolation condenser did not function, indicating that the AC powered isolation valves inside the primary containment vessel were closed.[40] Thus, the fundamental safety function of core cooling at Unit 1 was lost when the isolation condenser was stopped by the operators just before the tsunami, and the Unit 1 core heated up from that time.

Additionally, local measurements (in the reactor building) at 20:07 indicated that the reactor was still near the operating pressure of 70 bar (7 MPa), which prevented water injection by alternative methods that would only be possible below 8 bar (0.8 MPa).

[38] The fire protection system was designed primarily for fire suppression and flooding of the containment vessel, not for injection of water into the reactor.

[39] Cross-tie lines had been installed at the Fukushima Daiichi NPP nearly a decade earlier as a design enhancement for accident management. Sharing the functioning emergency power of Unit 6 was only possible for Unit 5, since these interconnections had been installed only between pairs of units, i.e. Units 1 and 2, Units 3 and 4, and Units 5 and 6.

[40] The valve positions were not clear to the operators owing to the uncertain timing and sequence of each type of power loss that would determine the status of isolation valves. All the isolation condenser valves would keep their position when the AC power was lost, but the AC powered isolation valves would close, by design, if the control power (i.e. DC power) was lost.

After several reports from the on-site emergency response centre on the status of Unit 1 and the other units, and following the approval of the Prime Minister, a nuclear emergency was declared by the Government of Japan at 19:03 on 11 March.[41]

In Unit 2, which was also without any indications of operation of the core cooling system and core pressure and temperature, the operators assumed the worst case scenario that the reactor core isolation cooling system was not operating and the Unit 2 core was heating up. At 21:01, the on-site emergency response centre informed government authorities that the Unit 2 core, without any cooling, was predicted to become uncovered at around 21:40. Following this prediction, the Prime Minister, as the Director General of the Nuclear Emergency Response Headquarters, issued an order at 21:23 on 11 March for the evacuation of the public within 3 km, and for sheltering within 3–10 km, of the site[42].

The uncovering of the Unit 1 core was indicated when high radiation levels were encountered in the Unit 1 reactor building by a team that was dispatched at 21:51 to confirm the status of the operation of the isolation condenser.[43] This was an indication of the severity of the conditions at the Unit 1 reactor and of possible core damage.

Deterioration in conditions in Unit 1 confinement

Following the confirmation of the loss of core cooling in Unit 1, further challenges to the other fundamental safety function — the confinement — became evident when the first reading of the containment vessel pressure became possible at 23:50 on 11 March. The containment vessel pressure had exceeded the maximum pressure considered in its design, and this information prompted the Site Superintendent to order preparations for venting of the Unit 1 containment vessel. This situation also warranted an emergency notification, based on an 'abnormal rise in primary containment vessel pressure', as defined in the regulations associated with the Nuclear Emergency Act [19].

The measurements of Unit 1's containment pressure recorded the highest values at 02:30 and 02:45 on 12 March.

Confirmation of Unit 2's status and focus on recovery of Unit 1's safety function

At 02:10 on 12 March, a team was able to enter the room where Unit 2's reactor core isolation cooling system equipment was located and read the parameters to determine the system's status. The operating status was communicated to the on-site emergency response centre at 02:55 on 12 March and served to clarify the previously unknown condition of Unit 2 core cooling about 11 hours after the loss of monitoring in the main control room. On confirmation of Unit 2 core cooling, and with the acute challenge to the confinement function of Unit 1, the Site Superintendent decided to focus the accident management on venting efforts at Unit 1.

While the venting plans were being developed, the accident management strategy to restore Unit 1's core cooling using the fire pump for water injection proved to be impossible to implement because the pump was discovered to be inoperable at 01:48 on 12 March. The alternative, using fire trucks connected to the injection port in the turbine building, which had been installed the previous year as a

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[41] At the same time, the Nuclear Emergency Response Headquarters, located at the Prime Minister's Office, was established, and the Prime Minister assumed responsibilities as the Director General, directing the national nuclear emergency response.

[42] Earlier, at 20:50, the local government of Fukushima Prefecture had issued an evacuation order for residents within 2 km of the plant after evaluating the national nuclear emergency declaration and discussing the uncertainty concerning the status of the NPPs with TEPCO officials.

[43] Their personal dosimeters recorded levels as high as 0.8 mSv in about ten seconds of their stay in the building.

fire protection measure based on the experience of the Niigata-Chuetsu-Oki earthquake, was then put into action.

Heating up of Unit 5 and restoration of AC power

At about the same time, a Unit 5 safety relief valve automatically opened for the first time approximately 10 hours after the station blackout because the reactor pressure reached its opening set value, at 01:40 on 12 March. The valve automatically opened and closed several times to maintain the pressure in a range determined by the design because the Unit 5 reactor had continued to heat up in the absence of heat removal measures.

The safety relief valves were operating automatically to limit pressure, but could not be used to reduce pressure, since most of them had had their depressurization function disabled for the test carried out before the accident. Reducing pressure by opening a small valve (the head vent nozzle) on the reactor vessel was considered as an alternative because DC power was available for this purpose. Later, at 06:06 on 12 March, approximately 14.5 hours after the station blackout, the head vent nozzle was remotely opened and left open to depressurize the water-filled reactor vessel. In addition, the power connection between Unit 5 and the operating emergency diesel generator in Unit 6 was completed nearly 16.5 hours after the station blackout, enabling some AC power to be connected to the Unit 5 equipment, such as the pumps and valves needed for reactor heat removal.

Alternative cooling of the Unit 1 core

Meanwhile, the Unit 1 reactor pressure became low enough[44] to allow alternative water injection. An alternative cooling method, that is, freshwater injection from the fire engines into the Unit 1 reactor to restore core cooling, started at 04:00 on 12 March, about 12.5 hours after the station blackout. Water injection from a single one-tonne truck continued intermittently for approximately 5.5 hours with the truck having to return to the freshwater tank periodically to be refilled. At the same time, work on establishing a direct line from the tank continued. Later, just over 17.5 hours after the station blackout, continuous freshwater injection into Unit 1 started directly from the tank.

Venting of the Unit 1 containment

The measurement of Unit 1's containment pressure at 04:19 on 12 March showed that pressure in the containment had decreased since the last measurement (at 02:45) without any operator action and without an established vent path, indicating that some unintentional containment pressure relief had occurred through an unknown path. Furthermore, the radiation levels measured at the main gate shortly afterwards showed an increase[45]. This was also an indication of some uncontrolled radioactive release from the primary containment, i.e. degraded confinement. The deteriorating radiological conditions at the site, combined with the elevated containment pressure in Unit 1, caused the Government to expand the evacuation zone to 10 km at 05:44 on 12 March.

The activities to configure venting of Unit 1's containment were set to start at 09:00 on 12 March. As soon as confirmation was received from the Fukushima Prefecture authorities, at 09:02, of the completion of evacuation of Okuma Town[46], the teams were activated to start manipulation of the valves in order to arrange the path for the venting of Unit 1's containment. After 5.5 hours of efforts,

[44] Reactor depressurization had occurred without any operator or plant system actions, indicating that an unknown path provided pressure relief.

[45] An increase of around tenfold (0.000 069 mSv/h measured at 04:00 versus 0.000 59 mSv/h at 04:23).

[46] Completion of evacuation to start the venting was agreed with the Fukushima Prefecture authorities.

the venting path (Box 2.3) was established when the final valve on the path was opened at around 14:00 on 12 March. The success of the venting operation was confirmed by a decrease in containment pressures, as measured at 14:30[47], and was reported to the relevant government authorities. Although there was no significant immediate change in the radiation measurements within the site boundaries, about one hour later, a radiation dose rate reading of approximately 1 mSv/h was recorded at 15:29[48] by one of the site monitors located near the site boundary to the north-west of Unit 1.

Loss of normal core cooling and start of emergency core cooling in Unit 3

While the containment venting of Unit 1 was being established, the station blackout response in Unit 3 had to be modified when the reactor core isolation cooling system ceased to operate at 11:36 on 12 March, after nearly 20.5 hours of continuous operation. The operators tried unsuccessfully to restart the system several times, and the water in the reactor therefore continued to boil and evaporate and the reactor water level continued to decrease.

When the water level reached the point at which the high pressure coolant injection system — an emergency core cooling system — was activated automatically, at 12:35, this system automatically maintained the reactor water level in the predetermined range. However, the operators took manual control to avoid repeated automatic starts and stops of the system in order to preserve DC power for longer, in accordance with station blackout response procedures.

Seawater injection and power supply line-up for Unit 1

After approximately 11 hours of water injection into the Unit 1 core, the fresh water in the fire protection water tank was almost completely depleted. As a result, freshwater injection into Unit 1 was stopped at 14:53 on 12 March. The Site Superintendent then decided to inject sea water into the Unit 1 reactor from the Unit 3 backwash valve pit, where sea water had pooled after the tsunami, as it was the only available source of water at that time. The arrangements for seawater injection were completed in just over half an hour.

Around the same time, work to connect the mobile voltage power supplies[49] to Units 1 and 2 using an undamaged transformer in Unit 2 was completed, and a low voltage grid for supply of AC power to Unit 1 was re-energized at 15:30 on 12 March.

Nearly 24 hours after the station blackout, seawater injection and AC power supply were connected to Unit 1. However, within minutes of connection, an explosion in the Unit 1 reactor building damaged both of these arrangements before they could be put in use.

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[47] Overall, it took 14.5 hours from the Site Superintendent's order (around midnight) to start venting. This was a result of high radiation levels around the suppression chamber where valves had to be manually manipulated, and the lack of compressed air supply to operate the valves.

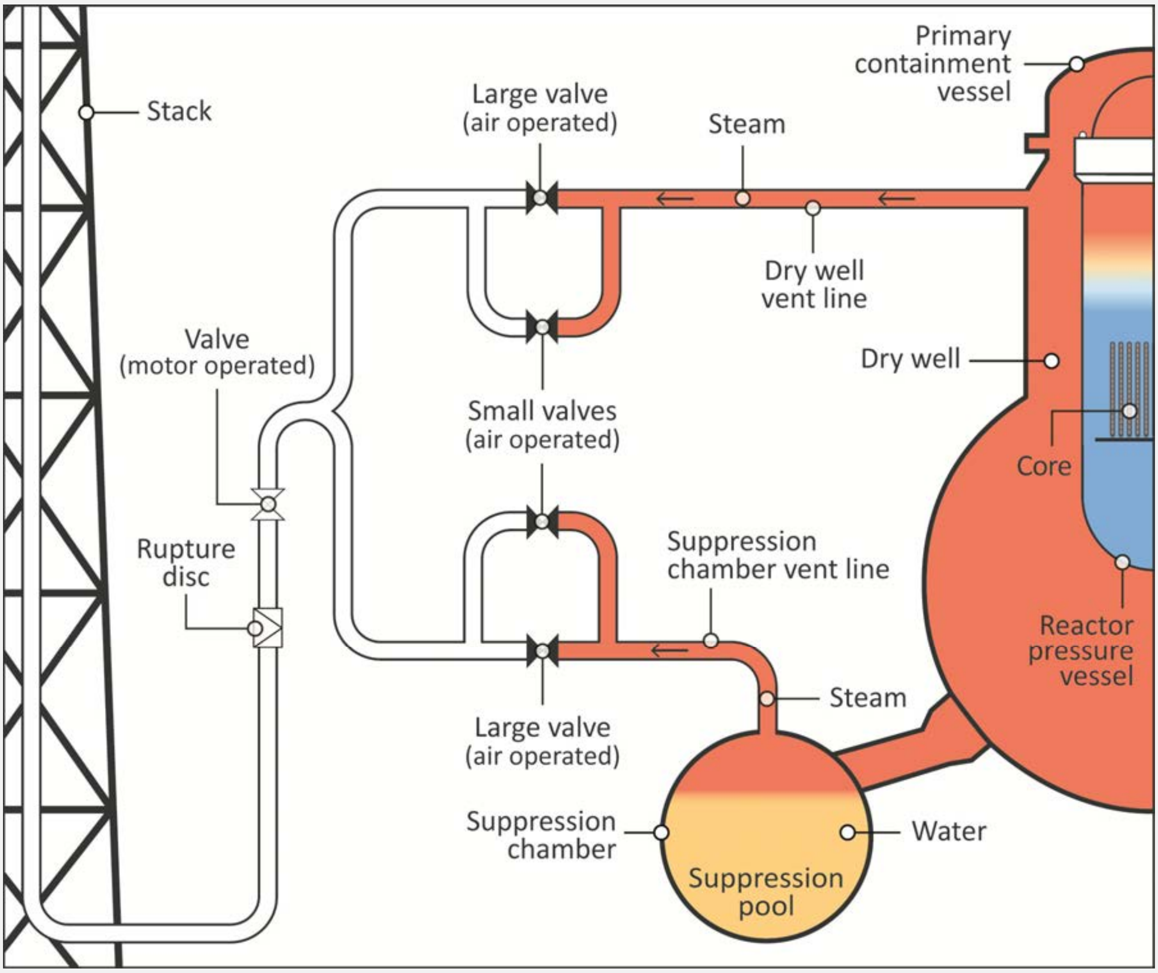
[48] At 16:17, it was noted by the emergency response centre that the radiation measurement taken at 15:31 near the main gate was 0.569 mSv/h, and the authorities were notified at 16:27 since the value exceeded the legal reporting criterion of 0.5 mSv/h. The notification was corrected at 16:53, when it was realized that the radiation level measured at 15:29 was 1.015 mSv/h, i.e. after venting of Unit 1 (but before the explosion at Unit 1).

[49] Almost one hour after the station blackout on 11 March, mobile power equipment (low and high voltage power supply vehicles) was dispatched to the Fukushima Daiichi and Fukushima Daini NPPs. The first vehicle, from Tohoku Electric, arrived around 22:00 on 11 March, i.e. nearly six hours after the station blackout. More vehicles from other TEPCO and Tohoku Electric facilities and the Japan Self-Defense Force arrived at the sites throughout the night. By 10:15 on 12 March, a total of 23 vehicles were at the site.

Box 2.3. Containment venting

As a measure to improve the ability to cope with severe accidents, 'hardened vents' (i.e. pressure relief devices with relatively thick walled discharge piping) were installed in the units at the Fukushima Daiichi NPP in the 1990s following a regulatory decision [22, 23]. The aim was to prevent overpressurization of the primary containment by allowing venting (see the figure below). Although the preferred path of venting was from the suppression chamber, in order to benefit from the removal of radioisotopes by the water pool, the vent path included another route from the dry well. Either path could be aligned by manipulating valves from the main control room, controlling the amount and duration of the release through a stack shared between the pair of units.

In the Fukushima Daiichi NPP, the vent line also contained a rupture disc that was set to break when the containment pressure exceeded a pre-set pressure, thereby preventing premature venting. The underlying philosophy in Japan was not to vent until it was inevitable, and as a last resort for maintaining the integrity of the primary containment in order to delay or prevent the direct release of radioactive material to the environment.



Explosion in the Unit 1 reactor building

At 15:36 on 12 March, an explosion occurred on the service floor of the Unit 1 reactor building, causing damage to the upper building structure and injuring workers. Although the explosion did not seem to damage the primary containment, there was extensive damage to the secondary containment (the reactor building). The cause of the explosion was unknown to the plant staff, but it was suspected that hydrogen had been released from the core and had escaped from the primary containment via an unknown path. Consequently, the on-site emergency response centre requested evacuation of staff from the areas in and around Units 1–4, including the two main common control rooms, except for the three most senior level staff.

Approximately three hours after the explosion in Unit 1 (four hours after venting of the Unit 1 containment), at 18:25 on 12 March, the Government extended the evacuation zone to 20 km.

Injection of sea water into Unit 1

The explosion in Unit 1 not only caused serious damage to the seawater injection and temporary electrical power line assemblies, but also hindered their repair because of the rubble scattered around the site and the locally high dose rates from contaminated rubble. After an evacuation lasting about two hours, teams returned to repair or replace damaged equipment.

After the repair and replacement of damaged equipment, water injection into the Unit 1 reactor, using fire engines and sea water from the Unit 3 backwash valve pit, started at 19:04 on 12 March and continued[50] afterwards. Boric acid was added later to address re-criticality concerns for ensuring the fundamental safety function of reactivity control. Overall, between the end of freshwater injection and the start of seawater injection, the Unit 1 core was without cooling for nearly four hours.

Loss of Unit 3 core cooling

While Unit 1 was assigned the highest priority with respect to the maintenance of the fundamental safety functions during the first day and a half after the earthquake and the tsunami, the core cooling situation in Unit 3 became a cause of concern on the morning of Sunday 13 March.

After 14 hours of continued operation of the emergency high pressure coolant injection system, the Unit 3 operators became concerned about the reliability and possible failure of the system's turbine powering the injection pump, which was by then operating at low reactor steam pressure. The concern was related to the possibility of turbine damage and the creation of a release path from the reactor vessel. This would result in an uncontrollable release of radioactive steam directly outside the primary containment. This concern was heightened when the turbine did not automatically stop, as it was designed to, when the reactor pressure decreased below the automatic shutoff pressure.

Consequently, the operators decided to stop the high pressure coolant injection system and instead use the alternative means of injection at low pressure (the diesel driven fire pump). The operators thought this could be achieved without interruption of core cooling, since the reactor pressure was already below that of the diesel driven fire pump and could be kept low by the use of pressure relief valves. The Unit 3 emergency high pressure core injection system was therefore turned off by the operators, who then started their attempts to open the pressure relief valves.

However, all attempts to open the pressure relief valves failed, and reactor pressure quickly increased above the level at which the diesel driven fire pump could inject, stopping the cooling of the Unit 3 core about 35 hours after the station blackout. Faced with this setback, the operators tried for nearly 45 minutes to return to injection via the emergency high pressure coolant injection system but were unsuccessful. Without any capability to cool the reactor, an emergency report for 'loss of reactor cooling function' as defined in the regulations associated with the Nuclear Emergency Act [19] was

[50] On one occasion, according to the investigations [7], a TEPCO executive who was representing the company at the Prime Minister's Office asked the Site Superintendent on the telephone to stop the seawater injection into Unit 1. That directive was not followed, and seawater injection was not interrupted.

issued for Unit 3 at 05:10 on 13 March. The Unit 3 core remained without cooling for the hours that followed, and Unit 3 became the next unit to lose core cooling.

After the loss of cooling, an alternative water injection method to cool the Unit 3 core utilizing the fire engines was ordered by the Site Superintendent at 05:15. In view of the deteriorating conditions, he also ordered the Unit 3 containment venting path to be lined up.

Unit 3 alternative core cooling and containment venting

The fire engines from Units 5 and 6 were dispatched to Unit 3 and work began at 05:21 on 13 March to establish a line for injecting sea water into the Unit 3 core from the Unit 3 backwash valve pit through the fire protection lines. An additional fire engine arrived from the Kashiwazaki-Kariwa NPP at 06:30. The seawater injection line was completed within an hour. However, its use was postponed by the Site Superintendent as a result of a communication from TEPCO Headquarters[51]. As a result, the injection line was changed back to the borated freshwater source through the fire protection line using fire engines.

The efforts to reduce the reactor pressure below the fire engine pump pressure in order to maintain water injection required the activation of the pressure relief valves. This was achieved by use of DC batteries from cars, which were collected in the common main control room of Units 3 and 4.

Meanwhile, the Unit 3 venting line arrangement was also completed in a little more than three hours, at 08:41 on 13 March, but the containment pressure was still below the containment design pressure, not high enough to cause the bursting of the rupture disc as designed. As efforts continued to reduce the reactor pressure by opening the safety relief valve, the operators in the main control room observed a drop in the reactor pressure in the Unit 3 reactor at 09:08, although the valve status indicators did not conclusively show whether or not the valves were in the open position. Along with this depressurization of the reactor vessel, there was a pressure surge in the primary containment, indicating a discharge from the reactor vessel to the containment vessel. Eventually, at 09:20 on 13 March, the containment pressure exceeded the maximum design pressure of the containment and, subsequently, the containment pressure dropped rapidly, indicating that the venting of the Unit 3 containment had occurred as a result of the bursting of the rupture disc.

Following reactor depressurization, achieved by opening additional safety relief valves, the reactor pressure fell below the fire engine pump pressure, and injection of borated fresh water into the Unit 3 reactor started at 09:25, after more than four hours without cooling.

The venting of the Unit 3 containment was short lived when a valve on the vent line closed[52] because of the lack of sufficient air supply to keep it open. After 6.5 hours of effort, the valve was reopened by using a mobile compressor.

Unit 2 precautionary measures for fundamental safety functions

At around 10:15 on 13 March, as the conditions for maintaining the relevant fundamental safety functions in Units 1 and 3 became more difficult, the Site Superintendent ordered the containment

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[51] A division director in the emergency Off-site Centre at TEPCO Headquarters who attended a meeting in the Prime Minister's Office earlier asked the Site Superintendent on the telephone whether there was any fresh water available. He informed the Site Superintendent of the views of meeting participants, who were inclined to continue freshwater injection as long as possible. The Site Superintendent interpreted this communication as a directive not to inject sea water as long as fresh water was available.

[52] As was discovered two hours later.

vent path for Unit 2 to be pre-emptively established. This was intended to take advantage of the still favourable radiological conditions, compared with the other units and site-wide trend[53], to conduct work in the Unit 2 reactor building where the valves were to be manipulated. The work was accomplished in 45 minutes, but venting did not occur because the pressure inside the Unit 2 containment was not high enough to burst the rupture disc.

At around 12:05, the Site Superintendent also ordered precautionary preparations for seawater injection into Unit 2 in case the unit's operating cooling system failed. For this purpose, fire engines were to be connected to the fire protection lines of Unit 2 to inject water from the backwash valve pit of Unit 3, if needed.

Injection of sea water into Unit 3 and increase of radiation levels

As the fresh water from the fire protection tanks was depleted at 12:20 on 13 March, the Site Superintendent decided to inject sea water into the Unit 3 reactor. The fire engines were repositioned, and seawater injection from the backwash valve pit of Unit 3 started nearly one hour later, at 13:12.

At 14:15 on 13 March, a high radiation dose rate (nearly 1 mSv/h) was measured near the site boundary, and the relevant government agencies were notified at 14:23 of an 'abnormal site boundary radiation level increase' as defined in the regulations associated with the Nuclear Emergency Act [19]. Fifteen minutes later, the radiation dose rate exceeded 100–300 mSv/h at the entry doors of the Unit 3 reactor building. As the dose rates measured on the Unit 3 side of the common main control room of Units 3 and 4 exceeded 12 mSv/h, the shift team moved to the Unit 4 side.

The on-site emergency response centre inferred from these dose levels that radioactive gases had escaped from the Unit 3 reactor, which in turn meant that hydrogen had also escaped. Mindful of the possibility of a hydrogen explosion similar to the one at Unit 1, the Site Superintendent decided, at 14:45, to temporarily evacuate the workers from the common main control room of Units 3 and 4 and from the areas in the vicinity of Unit 3.

The evacuated areas also included the Unit 3 backwash valve pit area, halting the activities for water injection. The evacuation order was lifted at 17:00, and workers returned to the Unit 3 backwash valve pit area to continue the activities for water injection and venting.

Establishment of core cooling in Unit 5

Meanwhile, the power from the Unit 6 emergency diesel generator was connected at 20:48 on 13 March to the pump of Unit 5's normal, low pressure, heat removal system, and was activated at 20:54. A reactor water injection line to the reactor of Unit 5 through one of the two residual heat removal systems was lined up and interconnecting pipe valves to the makeup water condensate system were opened, 53 hours after the station blackout. However, water injection did not occur, since the reactor pressure had gradually risen and exceeded the injection pressure. In response, a safety relief valve was opened, making use of available DC power and nitrogen supplies. This was successful in reducing the pressure in the reactor pressure vessel and allowed water injection into the Unit 5 reactor at 05:30 on 14 March, which continued afterwards.[54]

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[53] Between 05:30 and 10:50 on 13 March, neutrons were detected about 1 km away from the reactor buildings of Units 1–4 near the main gate, indicating a possible breach of the containment vessel, although the source of the neutrons was unknown.

[54] In addition, the AC power to operate the system for controlling reactor building pressure was supplied from Unit 6's emergency diesel generator. A little over two days after the blackout, pressure in the reactor building was below atmospheric pressure, ensuring secondary confinement.

Loss of seawater cooling in Units 1 and 3

As the injection of sea water into Units 1 and 3 from the Unit 3 backwash valve pit continued into Monday, 14 March, the water in the pit fell to such a low level that injection had to be halted at 01:10. After the intake hose was lowered deeper into the pit, the remaining pit water was reserved for injection into Unit 3, which resumed two hours later. Unit 1 core cooling was postponed until the pit could be refilled.

In the following hours, the Unit 3 containment pressure was found to be increasing and the reactor water level indication continued to decrease. The reactor water level in Unit 3 went off-scale at 06:20 on 14 March, indicating to the operators that the core was uncovered. The Site Superintendent ordered an evacuation of all workers because of concern about a possible hydrogen explosion in Unit 3, halting the pit refilling activities.

The containment pressure in Unit 3 reached a maximum at 07:00, but was found to be slightly lower at 07:20. It subsequently remained stable below maximum design pressure. The Site Superintendent then decided to resume the work to establish a line to refill the backwash valve pit from the ocean. In the next two to four hours, the seawater injection lines for all units were re-established, and refilling of the pit commenced, utilizing two additional fire engines to pump water from the ocean and tanker trucks from the Japan Self-Defense Force, which arrived at the site at 10:26, to carry water to the pit.

Seawater injection into Unit 1 was ready to be resumed when all activities, including the ongoing seawater injection into the Unit 3 reactor, had to stop because of the explosion in Unit 3. This damaged the hoses and fire engines around the Unit 3 backwash valve pit and necessitated a temporary evacuation of workers from the outside areas.

Explosion in the Unit 3 reactor building

At 11:01 on 14 March, an explosion occurred in the upper part of the Unit 3 reactor building, destroying the structure above the service floor and injuring workers. In addition to the destruction of the alternative water injection arrangement, the capability to vent the containment in Unit 2 was also lost as a result of the explosion, which affected the previously set up Unit 2 containment venting path. After the explosion, the isolation valve on the Unit 2 vent line was discovered to be closed and could not be reopened.

Restart of seawater cooling in Units 1 and 3

The work to re-establish the seawater injection line, this time directly from the ocean, was started again after a break of two hours. After restoration of injection lines, seawater injection was recommenced first for Unit 3 in the afternoon of 14 March and later in the evening for Unit 1. The cores had been without cooling water injection for 5 hours in Unit 3 and for 18 hours in Unit 1.

Loss of cooling and seawater injection in Unit 2

At around 13:00 on 14 March, Unit 2 became the next unit to experience loss of cooling, with measurements showing that the reactor water level had decreased and that the reactor pressure had increased. This pointed to the possible failure of the Unit 2 reactor core isolation cooling system, as inferred by the unit operators and the on-site emergency response centre. As a result, a 'loss of reactor cooling functions' report as defined in the regulations associated with the Nuclear Emergency Act [19] was issued for Unit 2.

After the failure of the reactor core isolation cooling system, seawater injection through the fire protection system was attempted at 13:05, but the reactor pressure was too high for the fire engine pumps. It seemed likely that, without water injection, the core would be uncovered very soon. It was therefore decided to use the relief valves to depressurize the reactor in order to enable water injection at low pressure, while recognizing the potential adverse impact on the confinement as a result of the release of steam from the reactor into the containment.[55]

After reactor vessel depressurization and refuelling of the fire engines, seawater injection into Unit 2 through the fire protection system began shortly before 20:00 on 14 March, first with one fire engine and soon afterwards with two.

Degradation of the Unit 2 confinement

At around 21:55 on 14 March, recently restored radiation monitoring equipment inside the containment indicated that the radiation levels in the Unit 2 containment had increased substantially since the previous measurements taken eight hours earlier.[56] Also, both the reactor and containment pressures showed an increasing trend after 22:30 on 14 March. The containment pressure exceeded the design pressure at 22:50, prompting an emergency declaration of an 'unusual rise of pressure in containment vessel' in accordance with the regulations associated with the Nuclear Emergency Act [19] for Unit 2. This condition was reported to the relevant government authorities at 23:39. Over the next three to four hours, more relief valves were opened to decrease reactor pressure in order to allow water injection into the Unit 2 reactor. As a consequence, the containment pressure increased further while the unit operations team tasked with establishing the venting line to relieve containment pressure was unable to open the vent valves. In order to protect the confinement function and permit venting as soon as possible, TEPCO staff at the emergency on-site and off-site centres agreed to vent directly from the dry well, recognizing that this would increase radioactive releases to the environment. However, it was not possible to open the valves on the dry well vent either, and consequently Unit 2 venting could not be accomplished.

At 04:17 on Tuesday 15 March, the relevant government agencies were notified that depressurization of the Unit 2 containment and of the reactor had not been effective and that containment pressure continued to increase.

Events in Units 2 and 4 followed by site evacuation

At 06:14 on 15 March, an explosion was heard on the site and tremors were felt in the common main control room of Units 1 and 2. This was followed by a drop in the pressure reading of the Unit 2 containment (suppression chamber). The staff in the main control room initially reported to the on-site emergency response centre that the Unit 2 suppression chamber pressure had dropped to near atmospheric pressure[57], indicating potential loss of the confinement function.

This information indicated a possible containment vessel failure and the possibility of uncontrolled releases from Unit 2. On this basis, the on-site emergency response centre ordered all personnel in all the units to temporarily evacuate to the seismically isolated building where the on-site emergency response centre was located. At about the same time as the event associated with the Unit 2

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[55] The suppression chamber section of the primary containment vessel was already nearly saturated.

[56] A 5000-fold increase in radiation levels in the containment atmosphere (from 1.08 mSv/h to 5360 mSv/h) and a 40-fold increase in radiation levels in the suppression pool section of the containment (from 10.3 mSv/h to 383 mSv/h). Additionally, neutrons had been detected between 21:00 on 14 March and 01:40 on 15 March, again near the main gate. It was thought by TEPCO that the neutrons came from the spontaneous fission of actinides that were released following core damage in one of the three reactors.

[57] After rechecking the readings, it was confirmed that the suppression chamber pressure was off the scale, but the dry well section pressure had not decreased significantly in Unit 2.

suppression chamber, an explosion in the upper part of the Unit 4 reactor building was reported by the evacuating personnel.

Following the events in Units 2 and 4, all personnel except those required for monitoring and emergency response were instructed by the Site Superintendent to go to a radiologically safe location. Approximately 650 people understood this order as a site evacuation and evacuated to the Fukushima Daini NPP. An estimated 50–70 staff[58], including the Site Superintendent, remained at the Fukushima Daiichi site. The relevant government agencies were informed of the evacuation by the on-site emergency response centre at 07:00 on 15 March.

About two hours later, white smoke (or steam) was observed being released from the Unit 2 reactor building near the fifth floor. A radiation dose rate measurement of nearly 12 mSv/h was recorded at the main gate at 09:00 on 15 March, the highest measurement since the beginning of the accident. Because of the high radiation levels, an order was issued by government authorities, two hours later, at 11:00, requiring all residents within a 20–30 km radius of the Fukushima Daiichi NPP to take shelter indoors.

During this sequence of events, fundamental safety functions of Units 1–3 were lost or severely degraded (Fig. 2.5), and efforts focused on damage assessment and restoration and stabilization of those functions.

2.1.3. Stabilization efforts

Replenishment of the spent fuel pool at Units 3 and 4

A remote visual inspection from a helicopter to address concerns about the status of the Unit 3 and 4 spent fuel pools was conducted in the afternoon of Wednesday, 16 March. The inspection confirmed that there was sufficient water in the Unit 4 spent fuel pool to cover the fuel assemblies; however, observations were not conclusive for Unit 3's spent fuel pool, making its replenishment a high priority.

The first supply of water to the Unit 3 spent fuel pool was made between 09:30 and 10:00 on 17 March, when helicopters dropped sea water. Fresh water was sprayed by water cannon trucks later on the same day between 19:05 and 20:07. Sea water or fresh water was sprayed into the Unit 4 spent fuel pool starting on 20 March[59].

Spraying into the pools using water cannon and fire engine trucks or concrete pump vehicles continued intermittently in March, to ensure that the spent fuel was not exposed. The fuel pool cooling and cleanup system was also utilized in April and well into May 2011.

Restoration of power supplies and end of the station blackout

Between 17 and 20 March, work was carried out to lay temporary power cables to Units 1 and 2. At 15:46 on Sunday 20 March, almost exactly nine days after the station blackout, off-site power was restored to Units 1 and 2 through this temporary AC power system, ending the blackout in Units 1 and 2.

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[58] As noted by different investigation reports, the exact number of staff is not certain [6, 8]. It is also noted that the staff who evacuated to the Fukushima Daini NPP site started to return to the Fukushima Daiichi NPP site on the same day.

[59] The same approach was followed for adding water to the spent fuel pool of Unit 1. Since the Unit 2 reactor building was still covering the Unit 2 spent fuel pool, the spray method could not be used for Unit 2.

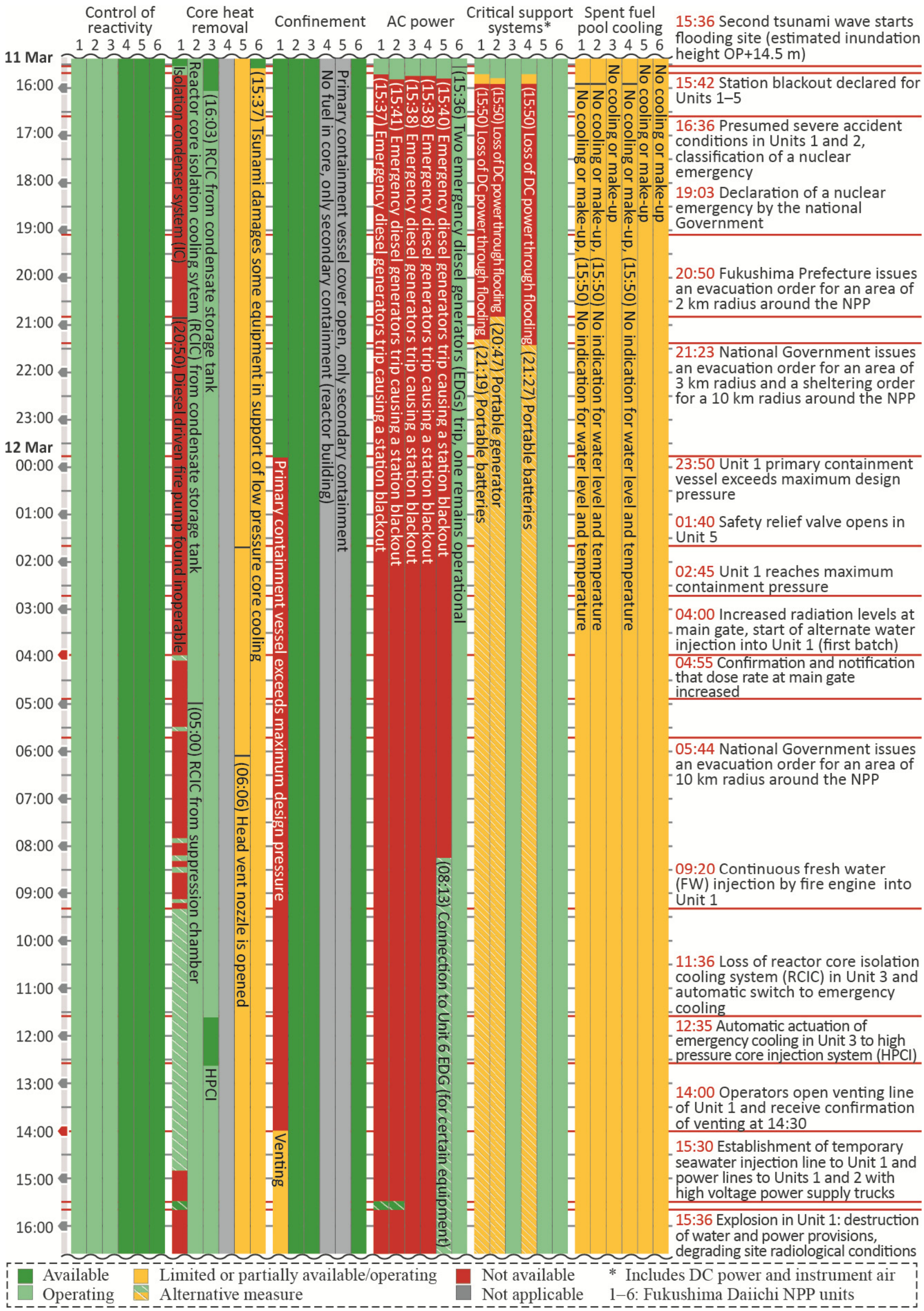

FIG. 2.5. Fundamental and supporting safety functions in the accident response at the Fukushima Daiichi NPP (11–15 March 2011).

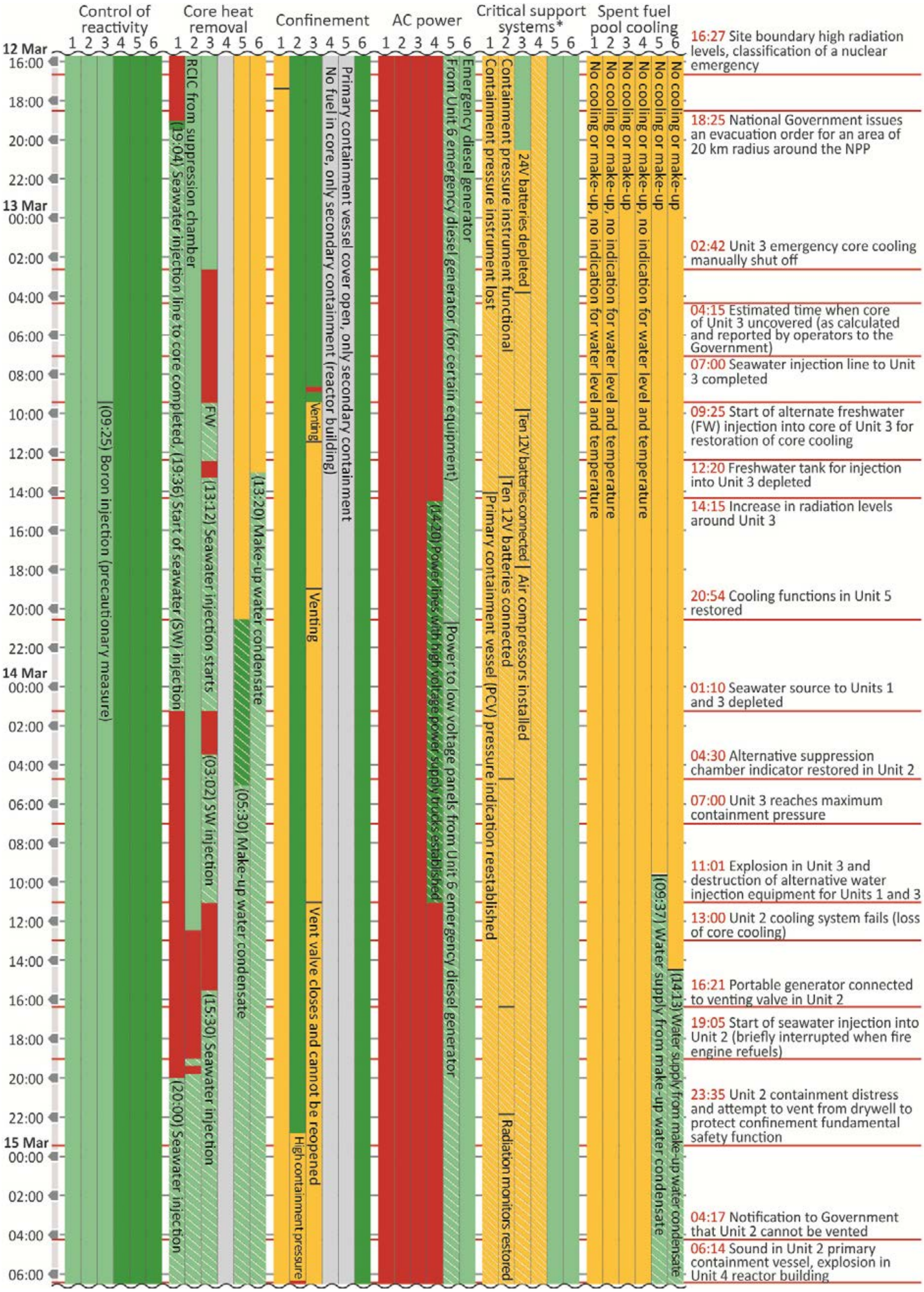

FIG. 2.5. Fundamental and supporting safety functions in the accident response at the Fukushima Daiichi NPP (11–15 March 2011) (cont.).

In Unit 6, power was restored to the cooling system of the second water cooled emergency diesel generator through a power line connected to the operating air cooled generator. The water cooled emergency diesel generator began operation again at 04:22 on 19 March, supplying AC power to Units 5 and 6.

The blackout at Units 3 and 4 ended after more than 14 days, when temporary off-site power to these two units was restored on 26 March.

Achieving stable conditions

Unit 5 was the first unit to reach cold shutdown mode when its normal residual heat removal system was put into service, at 12:25 on 20 March. The reactor temperature decreased below 100°C in approximately two hours, placing Unit 5 in the cold shutdown mode at 14:30 on 20 March 2011, nearly nine days after the beginning of the accident.

The normal residual heat removal system of Unit 6 was put back in service, in a manner similar to that at Unit 5, at 18:48 on the same day. The reactor temperature decreased below 100°C in less than one hour, placing Unit 6 in the cold shutdown mode at 19:27 on 20 March (Fig. 2.6).

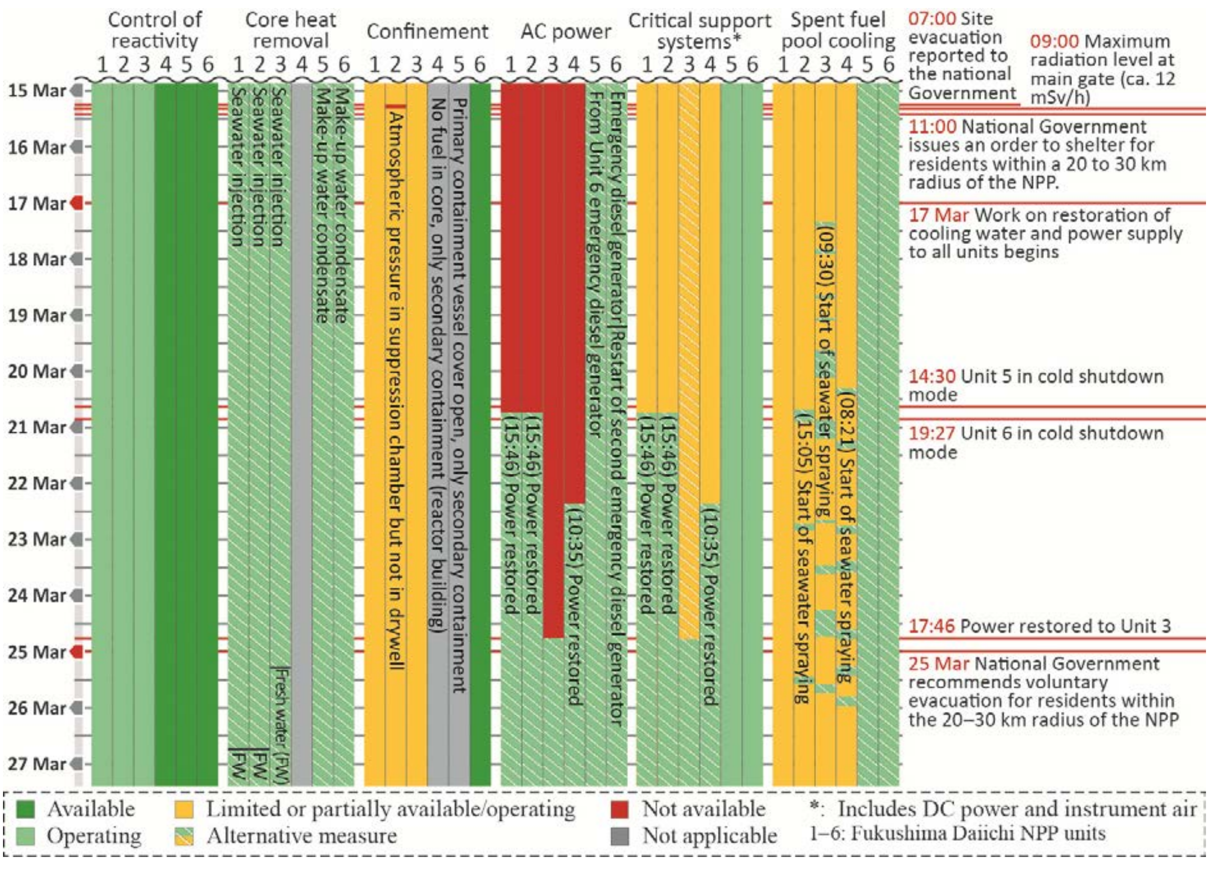

FIG. 2.6. Temporary restoration of fundamental safety functions at the Fukushima Daiichi NPP.

For Units 1–3, TEPCO issued an action plan on 17 April 2011, the Roadmap towards Restoration from the Accident at the TEPCO Fukushima Daiichi Nuclear Power Station [24]. The roadmap included measures to be taken for: the establishment of stable cooling of the reactors and spent fuel; reduction and monitoring of radioactive releases; control of hydrogen accumulation; and prevention of return to criticality. These actions were implemented in the nine months following the accident.

The roadmap established two conditions that would define the end of the accident state, or 'cold shutdown state'[60]: achievement of significant suppression of radiological releases and steady decline of radiation dose rates; and achievement of target values for certain plant parameters as prescribed in the roadmap. The Government of Japan and TEPCO announced on 19 July that the first condition had been achieved in Units 1–3 and, on 16 December 2011, that the second condition had been achieved for these units. This announcement officially[61] brought the 'accident' phase of events at the Fukushima Daiichi NPP to a close.

However, some unstable plant conditions continued, such as fluctuations in temperatures, which had been explained as being caused by instrumentation failures, or fluctuations in the measurement of fission products. More stable plant parameters were achieved between March and April 2012, while post-accident management efforts continued. Additionally, challenges in the management of waste, such as difficulties in dealing with the accumulation of radioactive water due to groundwater ingress to the buildings and occasional failures of equipment, continued. At the time of writing, the Government of Japan considered the Fukushima Daiichi NPP a 'specified facility as an accident site'[62].

2.2. NUCLEAR SAFETY CONSIDERATIONS

2.2.1. Vulnerability of the plant to external events

The earthquake on 11 March 2011 caused vibratory ground motions that shook the plant structures, systems and components. It was followed by a series of tsunami waves, one of which inundated the site. Both the recorded ground motions and the heights of the tsunami waves significantly exceeded the assumptions of hazards that had been made when the plant was originally designed. The earthquake and the associated tsunami impacted on multiple units at the Fukushima Daiichi NPP.

The seismic hazard and tsunami waves considered in the original design were evaluated mainly on the basis of historical seismic records and evidence of recent tsunamis in Japan. This original evaluation did not sufficiently consider tectonic-geological criteria and no re-evaluation using such criteria was conducted.

Prior to the earthquake, the Japan Trench was categorized as a subduction zone with a frequent occurrence of magnitude 8 class earthquakes; an earthquake of magnitude 9.0 off the coast of Fukushima Prefecture was not considered to be credible by Japanese scientists. However, similar or higher magnitudes had been registered in different areas in similar tectonic environments in the past few decades.

There were no indications that the main safety features of the plant were affected by the vibratory ground motions generated by the earthquake on 11 March 2011. This was due to the conservative approach to earthquake design and construction of NPPs in Japan, resulting in a plant that was provided with sufficient safety margins. However, the original design considerations did not provide comparable safety margins for extreme external flooding events, such as tsunamis.

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[60] The term 'cold shutdown state' was defined by the Government of Japan at the time specifically for the Fukushima Daiichi reactors. Its definition differs from the terminology used by the IAEA and others.

[61] According to the criteria set by the Government of Japan at the time.

[62] In accordance with the definition of 'specified nuclear facility', i.e. a facility that would require special measures for safety or physical protection of specified nuclear material, established by the current regulatory body, the Nuclear Regulation Authority (NRA), on 7 November 2012.

The vulnerability of the Fukushima Daiichi NPP to external hazards had not been reassessed in a systematic and comprehensive manner during its lifetime. At the time of the accident, there were no regulatory requirements in Japan for such reassessments and relevant domestic and international operating experience was not adequately considered in the existing regulations and guidelines. The regulatory guidelines in Japan on methods for dealing with the effects of events associated with earthquakes, such as tsunamis, were generic and brief, and did not provide specific criteria or detailed guidance.

Before the accident, the operator had conducted some reassessments of extreme tsunami flood levels, using a consensus based methodology developed in Japan in 2002, which had resulted in values higher than the original design basis estimates. Based on the results, some compensatory measures were taken, but they proved to be insufficient at the time of the accident.

In addition, a number of trial calculations were performed by the operator before the accident, using wave source models or methodologies that went beyond the consensus based methodology. Thus, a trial calculation using the source model proposed by the Japanese Headquarters for Earthquake Research Promotion in 2002, which used the latest information and took a different approach in its scenarios, envisaged a substantially larger tsunami than that provided for in the original design and in estimates made in previous reassessments. At the time of the accident, further evaluations were being conducted, but in the meantime, no additional compensatory measures were implemented. The estimated values were similar to the flood levels recorded in March 2011.

Worldwide operating experience has shown instances where natural hazards have exceeded the design basis for an NPP. In particular, the experience from some of these events demonstrated the vulnerability of safety systems to flooding.

Box 2.4. Tsunamis [25]

A tsunami — in Japanese meaning a wave (‘nami’) in a harbour (‘tsu’) — is a series of travelling waves of long wave length (e.g. from kilometres to hundreds of kilometres) and period (e.g. several minutes to tens of minutes, and, exceptionally, hours), generated by deformation or disturbances of the sea floor (or, in generic terms, underwater floor). Earthquakes, volcanic phenomena, underwater and coastal landslides, rock falls or cliff failures can generate a tsunami. Tsunamis can occur in all oceanic regions and sea basins of the world and even in fjords and large lakes.

Tsunami waves propagate outward from the generating area in all directions, with the main direction of energy propagation determined by the dimensions and orientation of the generating source. During propagation of the tsunami in deep water, they proceed as ordinary gravity waves, with a speed depending on the depth of water. For example, in deep ocean, speeds could exceed 800 km/h, with a wave height generally less than a few tens of centimetres and, in the case of an earthquake source, with wave lengths often exceeding 100 km. During the propagation, submarine topography affects the speed and height of the tsunami wave. Refraction, reflection from a sea mount or its chain (archipelago) and diffraction are important factors affecting the propagation of tsunami waves in deep water.

Tsunami waves become steeper and increase in height on approaching shallow water because wave speed is reduced and wave length is shortened when the depth decreases. In a coastal zone, local topography and bathymetry, such as a peninsula or submarine canyon, may cause an additional increase in wave heights which can also be amplified by the presence of a bay, an estuary, a harbour or lagoon funnels as a tsunami moves inland. Several large waves may occur and the first may not be the largest. A recession of the sea may also occur before the first wave and between each consecutive flooding. A tsunami may cause inland inundation because its wave length is so long that a huge mass of water follows behind the wave front. This can have a destructive impact.

The IAEA safety standards in force at the time of the accident required that before the construction of an NPP, site specific external hazards, such as earthquakes and tsunamis, need to be identified, and the impacts of these hazards on the NPP need to be evaluated as part of a comprehensive and full characterization of the site [26]. Adequate design bases are required to be established to provide sufficient safety margins over the lifetime of the NPP [27]. These margins need to be sufficiently large to address the high level of uncertainty associated with the evaluation of external events. Site related hazards also need to be periodically reassessed in order to identify any need for change as a result of new information and knowledge during the life of the plant [26].

In the 1960s and 1970s, it was common international practice to use historical records when applying methods for estimating seismic and concomitant (e.g. tsunami) hazards. This common practice included increasing safety margins by increasing the maximum recorded historical seismic intensity or magnitude in the site region and assuming that such an event would occur at the closest distance to the site [28]. This was done to account for the uncertainties in the observations of intensities or magnitudes, as well as to compensate for the fact that the maximum potential values might not be attained in a relatively short period of observation when, typically, the observation period needs to include pre-historical data in order to provide robust estimates for the hazard assessment. However, the seismic hazard assessment for the design of Units 1 and 2 at the Fukushima Daiichi NPP was conducted mainly on the basis of regional historical seismic data without increasing the safety margins as described above. During the process of obtaining construction permits for the later units, a new methodology was applied using a combination of historical earthquake information and the geomorphological fault dimensions [16, 29].

The information regarding the ‘inland’ faults was taken from official sources as well as from specific surveys conducted by the operator, and conservative parameters were assumed in the analysis to predict the magnitude of a possible earthquake. For the Japan Trench, an earthquake of magnitude 8 class was originally estimated as the maximum event without (i) sufficient tectonic based justification and (ii) use of global analogues, and based largely on observed historical data.

Large magnitude earthquakes (M 9) had occurred elsewhere in the Pacific ‘ring of fire’, for example in Chile in 1960 and in Alaska in 1964, shortly before Fukushima Daiichi Unit 1 was given the construction licence. These earthquakes did not lead to a consensus among Japanese seismologists that such an event would be possible close to the shores of Japan in a tectonic environment similar to those that generated earthquakes in other areas of the Pacific tectonic plate.

In the original assessment of external flooding hazards used in the ‘Establishment Permit’ for the plant, the plant designers applied the methodology and criteria prevalent in Japan at the time, which were based on the study and interpretation of historical records of earthquakes and tsunamis. The distant tsunami that occurred following one of the world’s largest known earthquakes in Chile in 1960 was the event used for design purposes against external flooding. This event resulted in a tsunami height observed at Onahama Port in Fukushima Prefecture of 3.1 m above sea level.

With regard to the tsunami sources located at the Japan Trench off the eastern coast, there was a lack of historical records of tsunami flood levels at the location of the Fukushima Daiichi site, as well as a lack of evidence of the occurrence of earthquakes in the area offshore of the site. The absence of data on nearby tsunami sources supported the adopted maximum flood level of 3.1 m for design purposes. TEPCO did not consider large magnitude earthquakes that had occurred elsewhere and did not postulate them as a local tsunami source at the Japan Trench.

Despite the lack of regulatory requirements in Japan for conducting a reassessment of seismic hazards and tsunami hazards, TEPCO had conducted several reassessments over the lifetime of the Fukushima Daiichi NPP [30]. TEPCO and other operating organizations in Japan had reassessed tsunami flood levels using a methodology developed by the Japan Society of Civil Engineers and published in

2002 [31]. This methodology used a standard source model for near or local tsunamis, based on historical data, in which no earthquake generating a tsunami is assumed to occur along the Japan Trench offshore of the Fukushima Daiichi site. The assumption of the standard source model, as described above, was applied in all evaluations that were performed using this methodology.

The 2006 guidelines of the Nuclear Safety Commission of Japan (NSC) [32] required consideration of inter-plate earthquakes as well as inland crustal earthquakes. These guidelines on seismic safety and associated events were used for evaluating seismic hazards, but the guidelines on tsunami hazards included only generic and brief statements and did not provide specific requirements, criteria or methodology. These earthquakes were considered by TEPCO as magnitude 8 class during its 'back-checking' of seismic safety as requested by the Nuclear and Industrial Safety Agency (NISA). However, owing to the distance of the site from those inter-plate earthquakes, the approach provided smaller hazard values associated with this tectonic structure when compared with the inland seismogenic sources. Consequently, their impact on the ground motion hazard was not considered. At the time of the accident, TEPCO had not completed the re-assessment of the vulnerability of the plant to earthquakes and tsunamis.

In 2009, TEPCO estimated a value of 6.1 m for the maximum tsunami height, using the latest bathymetric and tidal data. As a result of this new estimate, some design changes were made at the Fukushima Daiichi NPP, notably raising the motors of the pumps used for the removal of residual heat. During the accident, this measure alone proved to be insufficient. No other safety measures had been implemented to enhance flood protection, such as measures to avoid the flooding of emergency diesel generators.

In addition to the reassessments employing the methodology of the Japan Society of Civil Engineers, trial calculations of the tsunami water flood levels were performed by TEPCO before the accident. One of these trial calculations [30] applied the source model proposed by the Headquarters for Earthquake Research Promotion, which used the latest information and considered different scenarios [30, 33]. This approach examined the potential of the Japan Trench off the coast of Fukushima Prefecture to cause tsunamis. It did not rely only on historical tsunami records for this part of the tectonic subduction zone.

The new approach, applied between 2007 and 2009, postulated an earthquake of magnitude 8.3 off the Fukushima coast. Such an earthquake could lead to a tsunami runup of around 15 m at the Fukushima Daiichi NPP (similar to the actual tsunami height on 11 March 2011), which would inundate the main buildings. On the basis of this new analysis, TEPCO, NISA and other organizations in Japan considered that further studies and investigations were needed. TEPCO and other electrical utilities requested the Japan Society of Civil Engineers to review the appropriateness of the tsunami source models; these efforts were in progress in March 2011.

TEPCO did not take interim compensatory measures in response to these increased estimates of tsunami height, nor did NISA require TEPCO to act promptly on these results [30].

Notwithstanding the difficulties and uncertainties in the seismic hazard assessment, the events at the Fukushima Daiichi NPP demonstrated the robustness of Japanese NPPs in relation to earthquake vibratory ground motions. On 11 March 2011, the maximum accelerations recorded at the base mat of the reactor buildings of Fukushima Daiichi Units 1–5 were significantly larger than had been estimated when the plant was designed. However, there were no indications that the ground motion caused notable damage to safety related structures, systems or components [34]. However, the defences against tsunami induced flooding proved inadequate against tsunami wave heights that were much larger than those used in the design of the Fukushima Daiichi NPP. A scenario involving simultaneous extreme natural hazards and affecting multiple units was not considered in the design of the Fukushima Daiichi NPP. The timely provision of resources for the implementation of severe accident management actions at the Fukushima Daiichi NPP was compromised by the disruption off-site at the regional level due to the extensive damage caused to the infrastructure by the earthquake and the tsunami.

NPP operating experience in Japan and elsewhere in the 12 years prior to the accident showed the potential for severe consequences from flooding. The relevant operating experience included: a storm surge causing flooding at two reactors at the Le Blayais NPP in France in 1999; the Indian Ocean tsunami in 2004, which flooded seawater pumps at the Madras Atomic Power Station in India; and the Niigata-Chuetsu-Oki earthquake in Japan in 2007. The latter affected TEPCO's Kashiwazaki-Kariwa NPP, causing flooding of the reactor building of Unit 1 owing to the failure of the underground external fire extinguishing piping [35–38].

2.2.2. Application of the defence in depth concept

Defence in depth is a concept that has been applied to ensure the safety of nuclear installations since the start of nuclear power development. Its objective is to compensate for potential human and equipment failures by means of several levels of protection. Defence is provided by multiple and independent means at each level of protection.

The design of the Fukushima Daiichi NPP provided equipment and systems for the first three levels of defence in depth: (1) equipment intended to provide reliable normal operation; (2) equipment intended to return the plant to a safe state after an abnormal event; and (3) safety systems intended to manage accident conditions. The design bases were derived using a range of postulated hazards; however, external hazards such as tsunamis were not fully addressed. Consequently, the flooding resulting from the tsunami simultaneously challenged the first three protective levels of defence in depth, resulting in common cause failures of equipment and systems at each of the three levels.

The common cause failures of multiple safety systems resulted in plant conditions that were not envisaged in the design. Consequently, the means of protection intended to provide the fourth level of defence in depth, that is, prevention of the progression of severe accidents and mitigation of their consequences, were not available to restore the reactor cooling and to maintain the integrity of the containment. The complete loss of power, the lack of information on relevant safety parameters due to the unavailability of the necessary instruments, the loss of control devices, and the insufficiency of operating procedures made it impossible to arrest the progression of the accident and to limit its consequences.

The failure to provide sufficient means of protection at each of level of defence in depth resulted in severe reactor damage in Units 1, 2 and 3 and in significant radioactive releases from these units.

The earthquake on 11 March 2011 caused major damage to the infrastructure in the region, including the loss of connections from the off-site power grid to the Fukushima Daiichi NPP. This resulted in a deviation from the normal operation of the plant (defence in depth Level 1). After the earthquake, power supply was successfully provided from on-site sources, and all safety systems at defence in depth Level 3 continued to function as designed. This indicated that the safety systems and equipment withstood the seismic hazard [8].

The plant was built close to sea level and protection against flooding hazards was not sufficient, as the risk of flooding was not appropriately estimated [27]. Key safety equipment was not protected in leaktight compartments or by locating it at higher elevations to provide protection from flooding. This led to the loss of provisions for residual heat removal and containment cooling at defence in depth Levels 1, 2 and 3.

Box 2.5. The concept of defence in depth applicable at the time of the accident [27]

The concept of defence in depth, as applied to all safety activities, whether organizational, behavioural or design related, ensures that they are subject to overlapping provisions, so that if a failure were to occur, it would be detected and compensated for or corrected by appropriate measures. The concept has been further elaborated since 1988 [39, 40]. Application of the concept of defence in depth throughout design and operation provides a graded protection against a wide variety of transients, anticipated operational occurrences and accidents, including those resulting from equipment failure or human action within the plant, and events that originate outside the plant.

Application of the concept of defence in depth in the design of a plant provides a series of levels of defence (inherent features, equipment and procedures) aimed at preventing accidents and ensuring appropriate protection in the event that prevention fails.

(1) The aim of the first level of defence is to prevent deviations from normal operation, and to prevent system failures. This leads to the requirement that the plant be soundly and conservatively designed, constructed, maintained and operated in accordance with appropriate quality levels and engineering practices, such as the application of redundancy, independence and diversity. To meet this objective, careful attention is paid to the selection of appropriate design codes and materials, and to the control of fabrication of components and of plant construction. Design options that can contribute to reducing the potential for internal hazards (e.g. controlling the response to a postulated initiating event), to reducing the consequences of a given postulated initiating event, or to reducing the likely release source term following an accident sequence contribute at this level of defence. Attention is also paid to the procedures involved in the design, fabrication, construction and in-service plant inspection, maintenance and testing, to the ease of access for these activities, to the way the plant is operated and to how operational experience is utilized. This whole process is supported by a detailed analysis which determines the operational and maintenance requirements for the plant.
(2) The aim of the second level of defence is to detect and intercept deviations from normal operational states in order to prevent anticipated operational occurrences from escalating to accident conditions. This is in recognition of the fact that some postulated initiating events are likely to occur over the service lifetime of an NPP, despite the care taken to prevent them. This level necessitates the provision of specific systems as determined in the safety analysis and the definition of operating procedures to prevent or minimize damage from such postulated initiating events.
(3) For the third level of defence, it is assumed that, although very unlikely, the escalation of certain anticipated operational occurrences or postulated initiating events may not be arrested by a preceding level and a more serious event may develop. These unlikely events are anticipated in the design basis for the plant, and inherent safety features, fail-safe design, additional equipment and procedures are provided to control their consequences and to achieve stable and acceptable plant states following such events. This leads to the requirement that engineered safety features be provided that are capable of leading the plant first to a controlled state, and subsequently to a safe shutdown state, and maintaining at least one barrier for the confinement of radioactive material.
(4) The aim of the fourth level of defence is to address severe accidents in which the design basis may be exceeded and to ensure that radioactive releases are kept as low as practicable. The most important objective of this level is the protection of the confinement function. This may be achieved by complementary measures and procedures to prevent accident progression, and by mitigation of the consequences of selected severe accidents, in addition to accident management procedures. The protection provided by the confinement may be demonstrated using best estimate methods.
(5) The fifth and final level of defence is aimed at mitigation of the radiological consequences of potential releases of radioactive materials that may result from accident conditions. This requires the provision of an adequately equipped emergency control (see Section 3 on Emergency Preparedness and Response).

A relevant aspect of the implementation of defence in depth is the provision in the design of a series of physical barriers to confine the radioactive material at specified locations. The number of physical barriers that will be necessary will depend on the potential internal and external hazards, and the potential consequences of failures. The barriers may, typically for water cooled reactors, be in the form of the fuel matrix, the fuel cladding, the reactor coolant system pressure boundary and the containment.

The flooding was the common cause of failure of the emergency power supply system, the near complete loss of systems providing DC power to measuring and control devices, and the destruction of the structures and components providing seawater cooling for the plant.

The objectives of defence in depth Level 4 are the prevention of accident progression and the mitigation of the consequences of a severe accident. For actions at Level 4, the operators needed to use all available means to supply water to the reactor in order to ensure the adequate removal of residual heat. This required the availability of instruments which provide reliable information on the key safety parameters and simple, reliable means for pressure relief in the reactor. In addition, the operators needed clear guidance and to be trained to be able to initiate accident management measures [41].

As the accident progressed, operators lost the ability to reliably measure important safety parameters from the control room. This information was needed to assess the reactor status and to take well informed decisions on unusual actions and methods to cool the reactors. Nevertheless, the operators gave high priority to reactor cooling and managed to quickly prepare water supply lines with the intention of injecting coolant into the reactors using available low pressure pumps. However, the attempts to relieve reactor pressure failed because no provisions had been made to carry out this function after a complete loss of power. The required control power could not be restored in time to prevent core damage [8].

The last physical barrier included in defence in depth Level 4 is the reactor containment. Its purpose is to mitigate the consequences of accidents by preventing large radioactive releases to the environment after reactor damage. Depending on the containment type, various systems or kinds of equipment are needed to protect the containment against physical phenomena associated with core damage accidents that could challenge the containment integrity. The units at the Fukushima Daiichi NPP included means for the controlled venting of the containment to relieve the overpressure that might be caused by a steam leakage from the reactor cooling circuit. In addition, the atmosphere inside the containment was filled with inert nitrogen in order to eliminate hydrogen burn and prevent possible explosions.

Measurements taken during the accident indicate that the containment pressures of Units 1, 2 and 3 at certain times increased to levels that were near, or higher than, those for which the respective containments had been designed. This increase in pressure was due to the loss of containment cooling systems and the generation of steam by the overheated reactor cores. Although some containment venting systems were successfully opened, indications are that the containments of Units 1, 2 and 3 failed, leading to the release of radioactive material and hydrogen. The nitrogen atmosphere inside the containments had effectively prevented hydrogen burn and explosions from occurring in that confined space. However, as hydrogen leaked from the containments to the reactor buildings, hydrogen explosions occurred at Units 1, 3 and 4 [8].

The Fukushima Daiichi accident demonstrated that extreme natural hazards have the potential to invalidate or impair multiple levels of defence in depth [42, 43]. A systematic identification and assessment of external hazards and robust protection against these hazards needs therefore to be considered for all levels of defence in depth. Furthermore, the accident showed that alternative design provisions and accident management capabilities could still ensure the supply of cooling water to the reactor even if all prime safety systems designed to protect the reactor against accidents were lost. However, the timely use of such provisions requires instruments that can provide reliable information on the key safety parameters and simple, reliable means to relieve the pressure in the reactor, so that any means can be used to supply cooling water to the reactor.

2.2.3. Assessment of the failure to fulfil fundamental safety functions

The three fundamental safety functions important for ensuring safety are: the control of reactivity in the nuclear fuel; the removal of heat from the reactor core and spent fuel pool; and the confinement of radioactive material. Following the earthquake, the first fundamental safety function — control of reactivity — was fulfilled in all six units at the Fukushima Daiichi NPP.

The second fundamental safety function — removing heat from the reactor core and the spent fuel pool — could not be maintained because the operators were deprived of almost all means of control over the reactors of Units 1, 2 and 3 and the spent fuel pools as a result of the loss of most of the AC and DC electrical systems. The loss of the second fundamental safety function was, in part, due to the failure to implement alternative water injection because of delays in depressurizing the reactor pressure vessels. Loss of cooling led to overheating and melting of the fuel in the reactors.

The confinement function was lost as a result of the loss of AC and DC power, which rendered the cooling systems unavailable and made it difficult for the operators to use the containment venting system. Venting of the containment was necessary to relieve pressure and prevent its failure. The operators were able to vent Units 1 and 3 to reduce the pressure in the primary containment vessels. However, this resulted in radioactive releases to the environment. Even though the containment vents for Units 1 and 3 were opened, the primary containment vessels for Units 1 and 3 eventually failed. Containment venting for Unit 2 was not successful, and the containment failed, resulting in radioactive releases.

Box 2.6. Fundamental safety functions

The three fundamental safety functions are:

(1) Control of the reactivity;

(2) Heat removal;

(3) Confinement of radioactive material.

Prior to the accident at the Fukushima Daiichi NPP, there were two accidents involving the failure to maintain one or more of the fundamental safety functions. The accident in 1979 at the Three Mile Island NPP in the United States of America occurred as a result of the loss of the second of these safety functions, but radioactive releases to the environment were successfully prevented by the third function, confinement of radioactive material by the containment vessel. The accident in 1986 at the Chernobyl NPP in the former Soviet Union occurred as a result of the loss of the first of these safety functions. This plant did not have a containment vessel. Consequently, the Chernobyl accident resulted in a very large radioactive release to the environment. The Fukushima Daiichi accident occurred because of the loss of the second and third of these safety functions following a combination of extreme external events.

Control of the reactivity of nuclear fuel in the reactor core

The safety systems for controlling the reactivity of nuclear fuel in the reactor core are the reactor protection and the control rod drive systems. Prior to the earthquake, Fukushima Daiichi Units 1–3 were operating; Units 4–6 were shut down for maintenance. The reactors of Units 1–3 were automatically shut down by their reactor protection systems, which were activated by the seismic event monitoring equipment. The insertion of reactor control rods by the control rod drive systems terminated the nuclear chain reaction in the nuclear fuel and brought the reactors to a shutdown condition.

Removal of heat from the nuclear fuel

Following the shutdown of Units 1–3, residual heat, produced by the ongoing decay of radioactive substances in the fuel, was removed by the reactor cooling systems. This maintained the second fundamental safety function. These cooling systems comprised both closed circulation loops to transfer heat to the sea water and various means to inject water at high and low pressure into the reactor cores to remove this residual heat (see Section 2.1).

Many of these systems needed AC power to operate, and all of them needed DC power to control their operation. Most sources of power were lost during the course of the accident; this part of the report focuses on the impact of this loss of power.

Unit 1

The isolation condenser (see Box 2.2) for cooling Unit 1 started automatically as the result of a high reactor vessel pressure signal. It opened the isolation valves in the condensate return lines (other isolation valves in the lines were open during normal operation) when the reactor shut down following the earthquake. As required by the operating procedures, the isolation condenser system was stopped and restarted several times by the operators to prevent the reactor from cooling down too quickly and causing thermal stress exceeding the reactor pressure vessel design values. This was done by opening and closing the isolation valves in the condensate return lines [8].

At the time the tsunami inundated the site and electrical power was lost, the operators had just stopped the isolation condenser system by closing a valve on the return line outside the primary containment vessel. Operators had no information available on the isolation condenser valve positions, and it was not until approximately three hours later that they first attempted to manually restart the isolation condenser. The operators were not fully trained to understand how the valves worked under these conditions. They ultimately made two unsuccessful attempts from the main control room to restart the isolation condenser by opening the outer isolation valves. The operators had no procedures to manually operate the isolation condenser. At the time of writing, the exact location of all of the valves in the isolation condenser system was unknown, but indications are that the isolation condenser did not function following the tsunami [8].

The steam turbine operated high pressure coolant injection system was not available because its DC power was lost.

Following the loss of the isolation condenser and the high pressure coolant injection system, an alternative means of injecting water into the reactor pressure vessel that relied on low pressure equipment was needed, such as that provided by the pumps for firefighting or fire trucks. The operators prepared the injection pathways in due time, but to be able to inject water at low pressure, it was also necessary to reduce the pressure inside the reactor pressure vessel using the safety relief valves. These valves could not be opened because of the loss of control power and high pressure air. The pressure in both the reactor vessel and in the containment was too high to allow the injection of sufficient water to cool the fuel without venting the containment and depressurizing the reactor pressure vessel. The alternative low pressure water injection systems were thus incapable of injecting water into the reactor pressure vessel.

The pressure in the reactor vessel remained high until the core was severely damaged. The most likely cause of pressure relief was a breach of the reactor pressure vessel due to melting [44]. The assumption that pressure relief was caused by a breach is supported by the pressure increase in the containment a few hours after indications had been received of severe core damage. The consequent reduction in pressure provided the conditions for the first injection of water into the reactor pressure vessel about 12 hours after the tsunami. However, by this time, significant fuel damage had already occurred [8].

It is estimated that the damage to the reactor core occurred approximately 4–5 hours after the tsunami, and that the molten core breached the reactor vessel bottom about 6–8 hours after the tsunami. The first signs of radioactive release to the environment were observed about 12 hours after the tsunami, and a large release took place when the Unit 1 containment was vented to prevent its breach, because of the high pressure, about 23 hours after the tsunami. Chemical reactions between fuel cladding and water had generated large quantities of hydrogen, which passed from the reactor pressure vessel into the primary containment vessel and escaped further to the reactor building [8].

Unit 2

Unit 2 had a different design for removing residual heat from the reactor core. The reactor core isolation cooling system (see Box 2.2) used steam from the reactor pressure vessel to drive a turbine which pumped water into the reactor vessel. The Unit 2 reactor core isolation cooling system was manually started after off-site power was lost. To remotely operate this system, DC power was needed, and it was designed to operate for at least four hours. However, the system continued to operate in harsh conditions for about 68 hours without DC power and without operator interventions [8]. This system successfully maintained the water level in the reactor pressure vessel above the fuel and ensured the cooling function.

There are indications that, after about 68 hours, the reactor core isolation cooling system failed. It was therefore no longer possible to inject water into the reactor pressure vessel because it was at high pressure. The water level in the reactor pressure vessel was estimated to drop to the reactor core top in a few hours after the reactor core isolation cooling system stopped functioning. The operators relied on alternative equipment for the low pressure injection of water, similar to that available for Unit 1. After some initial difficulties, they succeeded in reducing the pressure in the reactor pressure vessel by using safety relief valves, although injection was too late to prevent the rapid heating of the fuel and damage to the reactor core.

The containment venting system failed to relieve the pressure at Unit 2. It is assumed that this failure occurred because the rupture disc did not break. It is estimated that the Unit 2 reactor core began to melt about 76 hours after the tsunami. Radioactive releases started about 89 hours after the tsunami, following the breach of the containment boundary as indicated by the rapid drop in containment pressure [45].

Unit 3

In Unit 3, DC power was available for about two days, in contrast to the situation in Units 1 and 2. This meant that the reactor core isolation cooling and the high pressure coolant injection systems using steam driven pumps were available. Initially, the operators were able to maintain water levels in the reactor core by injecting water with the reactor core isolation cooling system. They followed procedures that enabled them to maximize the battery life available for the reactor core isolation cooling system [8].

In addition, steam relief from the reactor pressure vessel to the suppression chamber was available, and the suppression chamber pressure could be controlled using spray water provided by fire pumps. This situation lasted for 20 hours, until the reactor core isolation cooling system stopped and could not be restarted. The high pressure coolant injection system started automatically injecting water into the reactor pressure vessel to maintain the water level.

The high pressure coolant injection system is intended to rapidly refill the reactor pressure vessel following a leak in the reactor coolant system. This system was very effective in reducing pressure in the reactor pressure vessel. However, this led to a situation where inlet steam pressure to the pump turbine dropped below the pump's specifications, and the efficiency of the pump decreased significantly. The operators decided to shut down the system after about 14 hours because of concerns that the system could fail and begin to leak radioactive material outside the containment.

Following the shutdown of the high pressure coolant injection system, operators prepared an injection line to the reactor vessel and were prepared to inject sea water into the reactor vessel. However, due to the high reactor pressure, it was not possible to inject sea water until the reactor was depressurized. Therefore, because of the delay in injecting sea water into the reactor vessel, the water level continued to drop close to the top of the fuel. It has been assessed that an automatic signal, suspected to be false, triggered the automatic fast depressurization by safety relief valves before the operators could open the safety valves in a more controlled manner [46]. The depressurization, together with the low water level in the pressure vessel, is estimated to have caused the remaining water in the reactor core to flash to steam, resulting in the loss of adequate core cooling. The subsequent series of events, leading to the loss of reactor core cooling, were similar to those at Unit 2.

The core started to overheat and the major steam discharge from the reactor pressure vessel to the containment suppression chamber increased the pressure to a level that caused the rupture disc in the vent line to burst, opening a release path to the environment [8]. Melting of the Unit 3 reactor core is estimated to have started about 43 hours after the tsunami. Large radioactive releases started about 47 hours after the tsunami [8].

Unit 4

Unit 4 was undergoing a scheduled inspection and was shut down before the accident. All fuel of Unit 4 was in the spent fuel pool at the time of the accident. Therefore, cooling of the Unit 4 reactor core was not necessary. Cooling of the spent fuel pool was not possible owing to the loss of electrical power, and as a result the pool temperature started to increase.

Spent fuel pools

In the first few days following the tsunami, the operators considered that there was sufficient water in the spent fuel pools and that overheating of the fuel was not an immediate issue. This view changed on 15 March, when the Unit 4 reactor building exploded. At the time, it was thought that the cause of the explosion was hydrogen, and the only possible source of hydrogen in Unit 4 was thought to be from overheated fuel in the spent fuel pool due to the loss of water cover. This immediately raised concerns about how much water remained in that pool, and efforts were made to determine the water level in the spent fuel pools.

On 16 March, visual inspections indicated that there was still water in the pool at Unit 4. However, concerns were raised about the status of Unit 3, which led to various mitigation efforts, including the airdrop of water from helicopters. Subsequent analysis and inspections revealed that the water level in the spent fuel pools of both Units 3 and 4 had not dropped to the level of the spent fuel. These inspections confirmed that the explosion in Unit 4 was caused by hydrogen, and that the source of the hydrogen was not the fuel in the Unit 4 spent fuel pool but the migration of hydrogen from Unit 3 to Unit 4 via a common ventilation system. However, the lack of knowledge about the actual conditions in the spent fuel pools during the accident, due to the loss of instrumentation, led to the effort to add water to the pool. A detailed description of the spent fuel pool events is given in Section 2.1.

Units 5 and 6

Units 5 and 6 were also affected by the tsunami, but their reactors were generating less residual heat, because they had been shut down for a considerable period prior to the accident. In addition, one of the emergency diesel generators at Unit 6 had survived the flooding and was operable. The operators therefore had more time to respond, and the cooling systems for both units were powered by the one remaining emergency diesel generator. This power supply maintained the cooling of the reactor cores and was eventually used to provide cooling to the spent fuel pools in Units 5 and 6, both of which were successfully cooled down to a safe condition [8].

Confinement of radioactive material and control of radioactive releases

As a result of the damage to the reactor cores in Units 1–3, large amounts of steam and hydrogen escaped the reactor pressure vessels. This, in turn, pressurized and heated the primary containment vessels. These vessels were breached and steam, hydrogen and other gases, together with radioactive material, were released into the reactor buildings and eventually to the environment.

The primary containment vessels of the reactors had not been designed to withstand the pressure that could be generated in a severe accident; because of this, venting systems had been installed in the 1990s [22, 23] to limit the pressure in the containment vessels in the event of an accident. There are indications that the primary containment vessels for Units 1–3 failed at various stages in the progression of the accident. This was the result of the pressure and temperature in the primary containment vessel rising to levels that were far in excess of their designed capability before venting could be implemented (see Section 2.1). The leakage of radioactive material from the reactor cores was partially mitigated by the suppression pools, which retained some of the radionuclides released from the reactor pressure vessels.

2.2.4. Assessment of beyond design basis accidents and accident management

Safety analyses conducted during the licensing process of the Fukushima Daiichi NPP, and during its operation, did not fully address the possibility of a complex sequence of events that could lead to severe reactor core damage. In particular, the safety analyses failed to identify the vulnerability of the plant to flooding and weaknesses in operating procedures and accident management guidelines. The probabilistic safety assessments did not address the possibility of internal flooding, and the assumptions regarding human performance for accident management were optimistic. Furthermore, the regulatory body had imposed only limited requirements for operators to consider the possibility of severe accidents.

The operators were not fully prepared for the multi-unit loss of power and the loss of cooling caused by the tsunami. Although TEPCO had developed severe accident management guidelines, they did not cover this unlikely combination of events. Operators had therefore not received appropriate training and had not taken part in relevant severe accident exercises, and the equipment available to them was not adequate in the degraded plant conditions.

In September 2012, the Nuclear Regulation Authority (NRA) was established. The NRA formulated new regulations for NPPs to protect the people and the environment, which came into force in 2013. These regulations strengthened countermeasures to prevent simultaneous loss of all safety functions due to common causes, including re-evaluation of the impact of external events such as earthquakes and tsunamis. New countermeasures for severe accident response against core damage, containment vessel damage and a diffusion of radioactive materials were also introduced.

The IAEA safety standards in force at the time of the accident required an assessment to be undertaken to determine whether safety functions could be fulfilled for all normal operational modes, accident conditions and beyond design basis accidents, including severe accidents. Important event sequences that could lead to a severe accident need to be identified using a combination of probabilistic methods, deterministic methods and sound engineering judgement [27]. In addition, specific deterministic beyond design basis accident analyses need to be performed to investigate credible accident scenarios that can be used to introduce improvements in accident management measures [41]. It is therefore necessary to determine whether safety functions can be fulfilled in beyond design basis accident conditions.

Box 2.7. Deterministic and probabilistic safety assessments [47, 48]

Safety analyses are analytical evaluations of physical phenomena occurring at NPPs. Deterministic safety analyses for an NPP predict the response to postulated initiating events. A specific set of rules and acceptance criteria is applied. Typically, these should focus on neutronic, thermohydraulic, radiological, thermomechanical and structural aspects, which are often analysed with different computational tools.

Best estimate deterministic safety analyses should be performed to confirm the strategies that have been developed to restore normal operational conditions at the plant following transients due to anticipated operational occurrences and design basis accidents. These strategies are reflected in the emergency operating procedures that define the actions that should be taken during such events. Deterministic safety analyses are required to provide the input that is necessary to specify the operator actions to be taken in response to some accidents, and the analyses should be an important element of the review of accident management strategies. In the development of the recovery strategies, to establish the available time period for the operator to take effective action, sensitivity calculations should be carried out on the timing of the necessary operator actions, and these calculations may be used to optimize the procedures.

Deterministic safety analyses should also be performed to assist the development of the strategy that an operator should follow if the emergency operating procedures fail to prevent a severe accident from occurring. The analyses should be used to identify what challenges can be expected during the progression of accidents and which phenomena will occur. They should be used to provide the basis for developing a set of guidelines for managing accidents and mitigating their consequences.

While deterministic analyses may be used to verify that acceptance criteria are met, probabilistic safety assessment (PSA) may be used to determine the probability of damage for each barrier. PSA may thus be a suitable tool for evaluation of the risk that arises from low frequency sequences that lead to barrier damage, whereas a deterministic analysis is adequate for events of higher frequency.

Deterministic safety analyses have an important part to play in the performance of a PSA because they provide information on whether the accident scenario will result in the failure of a fission product barrier. A PSA fault tree is a powerful tool that can be used to confirm assumptions that are commonly made in the deterministic calculation about the availability of systems.

The objectives of a PSA are to determine all significant contributing factors to the radiation risks arising from a facility or activity, and to evaluate the extent to which the overall design is well balanced and meets probabilistic safety criteria where these have been defined. In the area of reactor safety, PSA uses a comprehensive, structured approach to identify failure scenarios. It constitutes a conceptual and mathematical tool for deriving numerical estimates of risk. The probabilistic approach uses realistic assumptions whenever possible and provides a framework for addressing many of the uncertainties explicitly. Probabilistic approaches may provide insights into system performance reliability, interactions and weaknesses in the design, the application of defence in depth, and risks, that it may not be possible to derive from a deterministic analysis.

Improvements in the overall approach to safety analysis have permitted a better integration of deterministic and probabilistic approaches. With increasing quality of models and data, it is possible to develop more realistic deterministic analysis and to make use of probabilistic information in selecting accident scenarios. Increasing emphasis is being placed on specifying probabilistically how compliance with the deterministic safety criteria is to be demonstrated, for example, by specifying confidence intervals and how safety margins are specified.

Box 2.7. Deterministic and probabilistic safety assessments [47, 48] (cont.)

Several techniques can be used in performing a PSA. The usual approach is to use a combination of event trees and fault trees. The relative size (complexity) of the event trees and fault trees is largely a matter of preference of the analysis and also depends on the features of the software used.

The event trees outline the broad characteristics of the accident sequences that start from the initiating event and, depending on the success or failure of the mitigating safety and safety related systems, lead to a successful outcome or to damage to the core, or to one of the plant damage states (required for the Level 2 PSA). The fault trees are used to model the failure of the safety systems and the support systems to carry out their safety functions.

The fault trees should be developed to provide a logical failure model for the safety system failure states identified by the event tree analysis. The failure criterion that provides the top event of the fault tree for each safety system function should be the logical inverse of the accident sequence success criterion. The basic events modelled in the fault trees should be consistent with the available data on component failures. The fault tree models should be developed to the level of significant failure modes of individual components (pumps, valves, diesel generators, etc.) and individual human errors and should include all the basic events that could lead, either directly or in combination with other basic events, to the top event of the fault tree.

TEPCO started to perform probabilistic safety assessments, as well as some deterministic safety analyses of the more significant accident sequences, in the early 1990s. In line with the practice in IAEA Member States at that time, these probabilistic safety assessments were limited to events at single unit NPPs. Although the Fukushima Daiichi NPP was located in an area where tsunamis were possible, these analyses did not include common cause failures caused by flooding or extended loss of electrical power [8]. The probabilistic safety assessment studies for the Fukushima Daiichi NPP also did not consider internal flooding or fires, and the assumptions related to the operator's actions were optimistic.

A comprehensive probabilistic safety assessment, including internal flooding sequences, is needed to highlight the vulnerability to flooding of vital plant systems, such as emergency diesel generators and electrical switchgear. In 1991, a corroded pipe leaked water at a rate of 20 cubic metres per hour, which penetrated the room with the reactor's emergency power system through the door and cable penetrations at Unit 1 at the Fukushima Daiichi NPP. This event demonstrated the vulnerability to flooding with respect to the location of the emergency diesel generators and the electrical switchgear in the basement.

Accident management guidance had also been evaluated at the Fukushima Daiichi NPP through limited scope probabilistic safety assessment studies. For example, these assessments contained the use of the containment vent system through the application of a fault tree approach to simulate the equipment failures with a human error probability for manual operation. But there was no thorough assessment of the challenges in severe accident management, including the limited training and guidance provided to plant personnel. It was not recognized that assumptions about failure probability were overly optimistic and the studies did not lead to improvements in procedures and guidance [47] (see Box 2.8, on accident management).

The Fukushima Daiichi NPP had some weaknesses which were not fully evaluated by a probabilistic safety assessment, as recommended by the IAEA safety standards [47, 49]. Examples include the lack of protection for the emergency diesel generators, battery rooms and switchgear against flooding and the low likelihood of success of severe accident interventions, given the limited guidance, training and knowledge of plant personnel for severe accident management. Beyond design basis accidents were not sufficiently considered, which affected the capability to maintain cooling of the reactor core, the operators' ability to monitor important safety parameters and the management of the severe accident conditions (see Fig. 2.7).

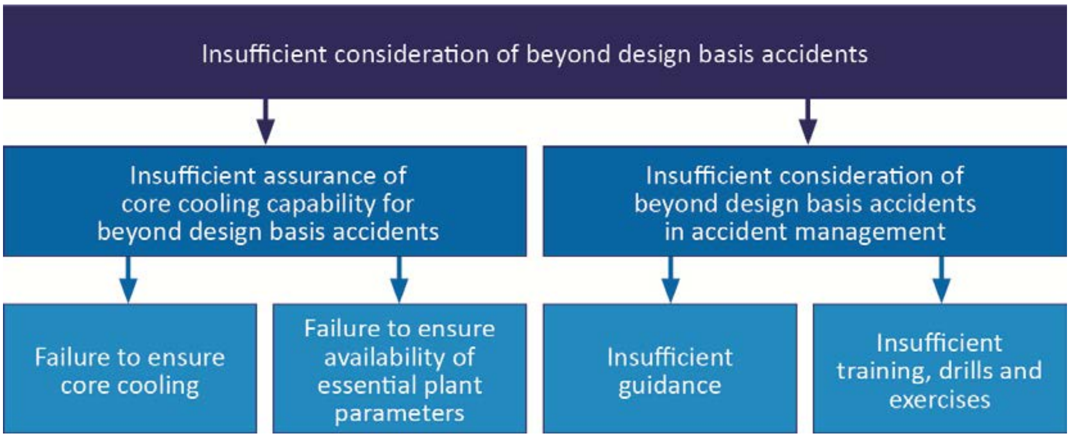


FIG. 2.7. Impact of the insufficient consideration of beyond design basis accidents affected the capability to maintain cooling of the reactor core, the operators' ability to monitor important safety parameters and the management of the severe accident conditions [27, 50].

Box 2.8. Accident management [41]

An accident management programme should be developed for all plants, irrespective of the total core damage frequency and fission product release frequency calculated for the plant. A structured top-down approach should be used to develop the accident management guidance. This approach should begin with the objectives and strategies, and result in procedures and guidelines, and should cover both the preventive and the mitigatory domains.

At the top level, the objectives of accident management are defined as follows: preventing significant core damage; terminating the progress of core damage once it has started; maintaining the integrity of the containment as long as possible; minimizing releases of radioactive material; achieving a long term stable state. To achieve these objectives, a number of strategies should be developed.

From the strategies, suitable and effective measures for accident management should be derived. Such measures include plant modifications, where these are deemed important for managing beyond design basis accidents and severe accidents, and personnel actions. These measures include repair of failed equipment. Appropriate guidance, in the form of procedures and guidelines, should be developed for the personnel responsible for executing the measures for accident management.

When developing guidance on accident management, consideration should be given to the full design capabilities of the plant, using both safety and non-safety systems, and including the possible use of some systems beyond their originally intended function and anticipated operating conditions, and possibly outside their design basis. The point at which the transition of responsibility and authority is to be made from the preventive to the mitigatory domain should be specified and should be based on properly defined and documented criteria.

For any change in the plant configuration, or if new results from research on physical phenomena become available, the implications for accident management guidance should be checked and, if necessary, a revision of the accident management guidance should be made.

The limited scope of the regulatory body's requirements for beyond design basis accidents contributed to the lack of proper consideration of relevant risks by plant operators. This was highlighted during an IAEA Integrated Regulatory Review Service (IRRS) mission in June 2007, which concluded that: "There are no legal regulations for the consideration of beyond the design basis [accidents], as Japanese plants are considered to be adequately safe as ensured by preventive measures" [51]. For example, the periodic safety review process in Japan did not require operating organizations to update their analyses to utilize the latest techniques [52].

The TEPCO accident management programme assumed that AC power would be promptly recovered at the Fukushima Daiichi NPP. TEPCO also assumed that other essential utilities, such as DC power and high pressure air, would be available at all times to provide power for instrumentation and to provide for the operation of valves. The programme and guidelines did not cover the possibility that a severe accident could affect several reactor units simultaneously or the possibility of difficulties in receiving support from outside the site because of serious disruption to the off-site infrastructure. This approach was in line with typical international practice at the time. The accident demonstrated that the operation of certain systems under beyond design basis conditions required exceptionally high skills on the part of the operators in order to maintain fundamental safety functions.

The accident management guidance in place at the Fukushima Daiichi NPP comprised a suite of documentation for use by the operators, including emergency operating procedures and severe accident management guidelines. Accident management guidelines were available for use by TEPCO technical support staff in the emergency response organization. Collectively, these documents covered the range of responses to design basis accidents and beyond design basis accidents, including severe accidents. The absence of electrical power and the lack of adequate information about the plant status made it difficult for the operators to effectively respond to the unfolding events. The accident management guidelines did not cover contingencies for the loss of instrumentation necessary to display the key parameters which allow operators to determine the status of the NPP. In addition, the guidelines did not provide recommendations for managing accidents when all safety related electrical distribution systems, and subsequently many of the dependent safety systems, were inoperable.

Personnel were not trained to perform accident management actions under conditions of prolonged station blackout or where information was limited or missing. Despite this, the operating staff performed their activities properly under the harsh conditions created by the accident. However, the inability to obtain fundamental information on the status of the plant and the need to improvise mitigation actions hampered the response. The absence of severe accident management requirements in the regulatory framework also contributed to the lack of preparation by TEPCO. The NSC published a guide on accident management in 1992 [23], and in the same year, the Ministry for International Trade and Industry (MITI) published a Roadmap of Accident Management. The Ministry also requested nuclear operating organizations to take actions to manage more severe accidents than those considered in the original design. However, this was not a mandatory requirement, and it resulted in limited voluntary actions by nuclear operating organizations. The IAEA IRRS mission to Japan in 2007 suggested the need for regulatory requirements for beyond design basis accidents, and suggested that NISA continue to develop a systematic approach to the consideration of such events, and also to the complementary use of probabilistic safety assessment and severe accident management [51]. The review mission's suggestions did not stimulate further efforts in this area.

2.2.5. Assessment of regulatory effectiveness

The regulation of nuclear safety in Japan at the time of the accident was performed by a number of organizations with different roles and responsibilities and complex inter-relationships. It was not fully clear which organizations had the responsibility and authority to issue binding instructions on how to respond to safety issues without delay.

The regulatory inspection programme was rigidly structured, which reduced the regulatory body's ability to verify safety at the proper times and to identify potential new safety issues.

The regulations, guidelines and procedures in place at the time of the accident were not fully in line with international practice in some key areas, most notably in relation to periodic safety reviews, re-evaluation of hazards, severe accident management and safety culture.

In the legal framework for nuclear safety applicable in Japan at the time of the accident, the Government had established main laws which were supplemented by subordinate laws and ministerial ordinances and statutes. The general structure of the legislative and regulatory framework at the time of the accident is illustrated in Figs 2.8 and 2.9. The regulatory structure in Japan at the time of the accident consisted of a number of Government departments and other organizations with responsibilities for nuclear safety. The structure had been revised twice, following the radiation incident aboard the nuclear powered ship *Mutsu* in 1974 and the criticality accident at JCO facility in Tokaimura in 1999, but some fundamental issues related to the clarity of roles and responsibilities had not been addressed [53, 54]. The IAEA IRRS mission in 2007 suggested the need to improve, refine and clarify a number of regulatory aspects [51], such as regulations regarding the treatment of beyond design basis accidents and clarification of the roles and responsibilities of NISA and the NSC within the Japanese regulatory system.

The Ministry of Economy, Trade and Industry (METI) was responsible for policy on the development and utilization of nuclear energy, as well as for the regulation of commercial nuclear installations. Within METI, the Agency for Natural Resources and Energy (ANRE) was responsible for overseeing the national energy supply, including promotion of nuclear energy. NISA was established in 2001 as a special agency attached to ANRE and given the responsibility as the nuclear safety regulatory body. The law required that, in case of conflict between safety and promotion, the Minister of METI should give priority to safety. METI established its National Strategic Plan based on this prioritization, and the IAEA IRRS mission in 2007 concluded that NISA was effectively independent of ANRE in its regulatory decision making. However, the mission also suggested that NISA's independence from METI be reflected more clearly in legislation.

The Ministry of Education, Culture, Sports, Science and Technology (MEXT) also had regulatory responsibilities, including oversight of radiation protection and nuclear material safeguards at NPPs, research reactors and certain research and development facilities for nuclear power. The Ministry also supervised the National Institute of Radiological Sciences (NIRS) and the Japan Atomic Energy Agency (JAEA).

The NSC, located in the Cabinet Office and reporting to the Prime Minister, was an independent body with both advisory and supervisory roles in the framework of nuclear regulation. It developed and issued the nuclear safety related policy documents and regulatory guides that were used by NISA in its regulatory work. The NSC was empowered by law to require reports from NISA and supervised NISA's work. It also had its own staff to carry out independent reviews and assessments of NPP licence applications and to re-confirm the conclusions made by NISA. The IAEA IRRS mission in 2007 suggested that the role of NISA as the regulatory body in relation to the NSC was in need of clarification.

NISA was supported by the Japan Nuclear Energy Safety Organization (JNES), which was established in 2003 under a law passed in 2002 [51]. JNES's main functions consisted of conducting inspections at nuclear facilities, reviewing the periodic inspections of licensees, providing nuclear emergency preparedness support and coordinating safety related research projects. A comprehensive inspection programme is needed for a regulatory body to be able to independently identify plant safety issues. In Japan at the time of the accident, despite NISA's efforts [56], inspections were rigidly structured, with the type and frequency specified by law. In 2011, Japan's report to the Convention on Nuclear Safety stated that the operators' safety management activities were governed by the operational safety inspections that NISA had approved. NISA conducted quarterly inspections to check operators' compliance with the periodic safety reviews. Periodic inspections were also conducted by NISA and JNES at intervals not exceeding 13 months, focused on the operators' maintenance of structures, systems and components of the NPPs. They concentrated on safety significant structures, systems and components, for example, those belonging to the reactor shutdown system, the reactor coolant pressure boundary, the residual heat removal system and the containment system. These regulatory procedures were in addition to the operators’ own walkdown and maintenance management of nuclear installations, periodic safety assessments, and technical evaluations related to NPP ageing. NISA had limited ability to expand inspections beyond the legally defined scope, which restricted its ability to identify deficiencies and deviations and ensure that lessons were learned [51]. This approach limited the effectiveness of regulatory inspection to identify safety issues and to verify the safety of licensees’ activities and their compliance with requirements.

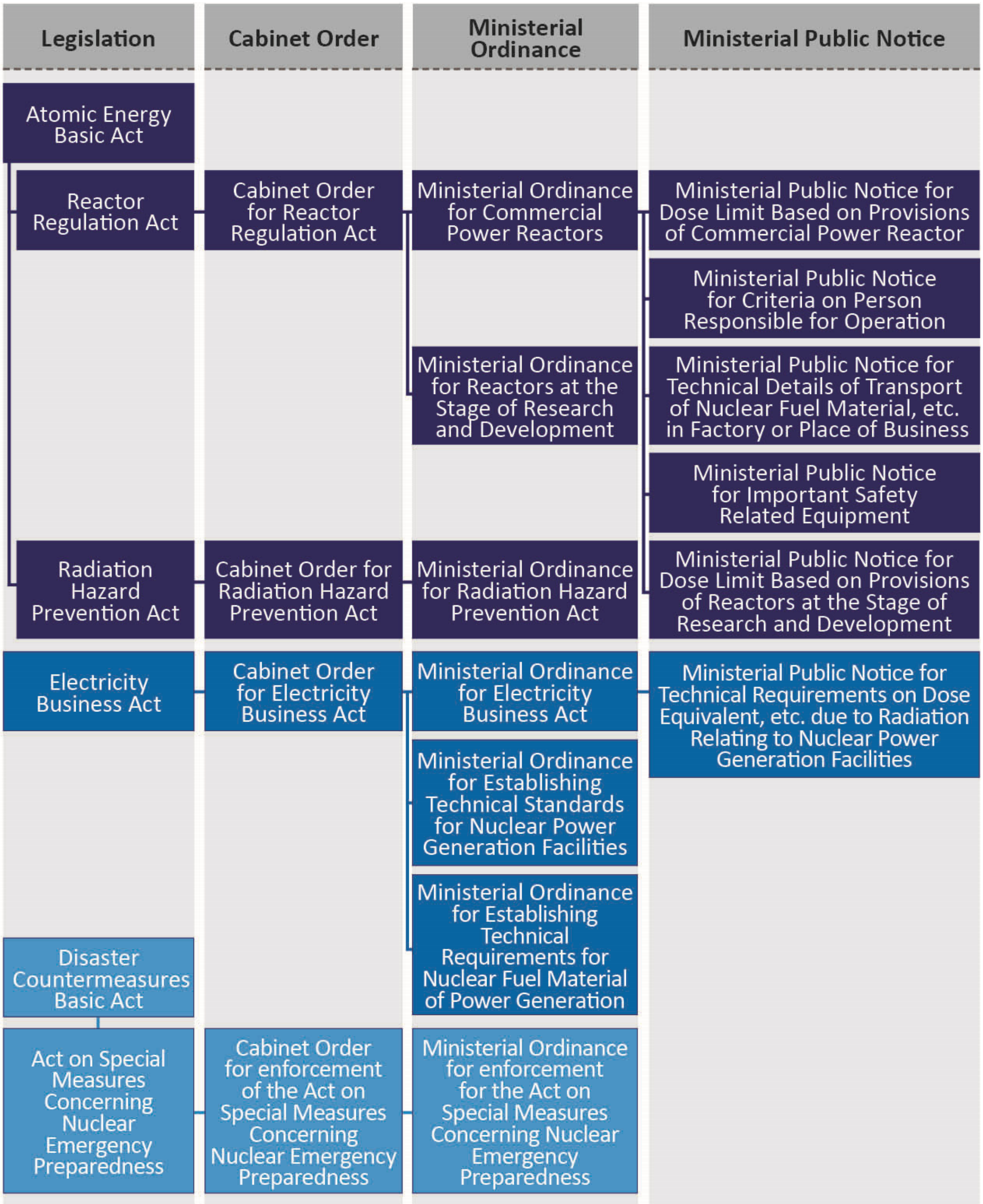


FIG. 2.8. The legislative and regulatory framework of nuclear installations safety in Japan at the time of the accident [55].

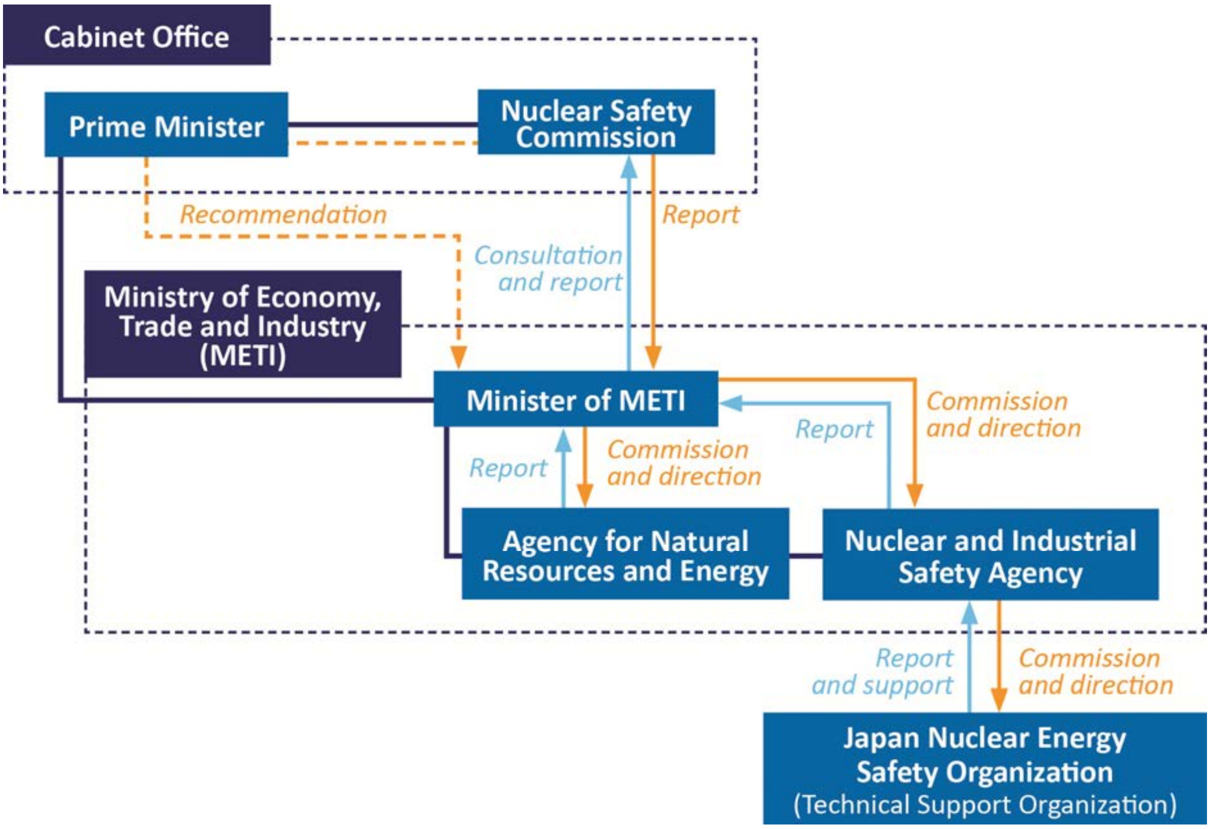


FIG. 2.9. Position of NISA in the Japanese Government.

A series of guidelines were issued by the NSC which were regarded, in practice, as requirements [34]. These guidelines were supplemented by consensus standards published by professional and academic societies. However, the regulations and guidelines in some key areas were not fully in line with international practice at the time of the accident. The most notable differences related to periodic safety reviews, re-evaluation of hazards, severe accident management and safety culture [52, 57, 58].

A periodic safety review provides a formal mechanism for re-examination by the licensees and the regulatory body of the design and external hazards in the light of new information and current standards and technology [52]. In Japan, periodic safety reviews at ten year intervals were required by regulations issued in 2003 [51], but these were of limited scope and not fully in line with international practice because they did not require a re-examination of external hazards [51, 52, 58].

The IAEA IRRS mission in 2007 suggested that NISA should be in a position to make a major contribution to the development of safety regulations. The mission also suggested that NISA needed the ability to modify its inspection programme in a flexible manner to optimize its effectiveness and focus and to be able to conduct safety inspections in locations and at times at its own discretion [51]. The IAEA IRRS mission also suggested that NISA foster frank and open relations with the nuclear industry and operating organizations in order to communicate regulatory concerns directly to the management level.

Establishment of the new regulatory authority

In September 2012, the Nuclear Regulation Authority (NRA) was established [59]. The NRA carried out a review of safety guidelines and regulatory requirements with the aim of formulating new regulations to protect people and the environment. In 2013, the new regulatory requirements for NPPs came into force. Based on the concept of defence in depth, importance was placed on the third and fourth levels and the prevention of simultaneous loss of all safety functions due to common causes. Previous assumptions on the impact of earthquakes, tsunamis and other external events such as volcanic eruptions, tornadoes and forest fires were re-evaluated, and countermeasures for nuclear safety against these external events were considered. Countermeasures against internal fires and internal flooding and enhancements of the reliability of on-site and off-site power to deal with the possibility of station blackout were also considered.

In addition, countermeasures for severe accident response against core damage, containment vessel damage and a diffusion of radioactive materials, enhanced measures for water injection into spent fuel pools, countermeasures for airplane crashes, and the installation of an emergency response building were also required.

Examples of new regulatory requirements in the light of the accident at the Fukushima Daiichi NPP include: (1) reinforced requirements for seismic/tsunami resistance; (2) reinforced or newly introduced requirements for design basis; and (3) newly introduced requirements for measures against severe accidents [60].

The roles and responsibilities that had previously been assigned to different governmental organizations were integrated into the NRA. The NRA holds jurisdiction over some of the activities of the NIRS and the JAEA. The main nuclear safety technical support organization JNES was merged with the NRA on 1 March 2014.

The NRA has adopted a periodic safety review process aligned with IAEA safety standards that was enforced in December 2013. The system requires nuclear power reactor licensees to comprehensively evaluate the safety of reactors and to submit the results to the NRA within six months of the end of periodic inspection, showing the following:

- The compliance with regulatory requirements;
- Measures for improving safety on a voluntary basis;
- Assessment and review of safety margins for improvement and a probabilistic risk assessment;
- Comprehensive re-evaluation based on the above results and action plans for improving safety.

Japan requested the IAEA to carry out an IRRS mission towards the end of 2015, aimed at strengthening nuclear safety and enhancing the NRA's competence as an independent nuclear regulator through a continuous, transparent and open learning process.

2.2.6. Assessment of human and organizational factors

Before the accident, there was a basic assumption in Japan that the design of NPPs and the safety measures that had been put in place were sufficiently robust to withstand external events of low probability and high consequences.

Because of the basic assumption that NPPs in Japan were safe, there was a tendency for organizations and their staff not to challenge the level of safety. The reinforced basic assumption among the stakeholders about the robustness of the technical design of NPPs resulted in a situation where safety improvements were not introduced promptly.

The accident at the Fukushima Daiichi NPP showed that, in order to better identify plant vulnerabilities, it is necessary to take an integrated approach that takes account of the complex interactions between people, organizations and technology.

Prior to the accident, there was not sufficient consideration of low probability, high consequence external events which remained undetected. This was in part because of the basic assumption in

Japan, reinforced over many decades, that the robustness of the technical design of the nuclear plants would provide sufficient protection against postulated risks. Consequently, the events that led to the accident at the Fukushima Daiichi NPP were outside the boundaries of the basic assumptions of the operating organizations, the regulatory body and the Government. These basic assumptions influenced the decisions and actions of a wide range of stakeholders, not limited to those directly involved in the operation and regulation of NPPs.

Box 2.9. Safety culture

In INSAG-4, a publication of the International Nuclear Safety Group (INSAG), safety culture was defined as: “that assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance” [61].

IAEA Safety Standard Series No. GS-G-3.5 [62] and Safety Reports Series No. 11 [63] make it clear that safety culture is itself a subset of the culture of the whole organization, with the latter comprising the mix of shared values, attitudes and patterns of behaviour that give the organization its particular character.

Organizations typically go through a number of phases in developing and strengthening safety culture. Safety Reports Series No. 11 identifies three stages:

(1) Safety is compliance driven and is based mainly on rules and regulations. At this stage, safety is seen as a technical issue, with compliance with externally imposed rules and regulations considered adequate for safety.

(2) Good safety performance becomes an organizational goal and is dealt with primarily in terms of safety targets or goals.

(3) Safety is seen as a continuing process of improvement to which everyone can contribute.

In reality, the three phases are not distinct, and any organization may have some parts that are ahead of others in the process of strengthening safety culture.

The basic assumptions influenced NISA not to exercise sufficient authority and, thus, NISA was not able to challenge other assumptions regarding nuclear safety. It was inhibited in the fulfilment of its oversight role by the lack of an appropriate regulatory framework and also by explicit legal constraints [6, 51]. For instance, the IAEA IRRS mission in 2007 found that NISA inspectors did not have unfettered access to licensees’ utilities to perform inspections and were only allowed to conduct inspections during certain times. Due to the basic assumption that the robustness of the technical design would provide sufficient protection against postulated risks, NISA generally worked in a less integrative and more reactive manner, in some cases being focused on short term activities, and did not address more fundamental and long term issues such as the consideration and application of IAEA safety standards. In some cases, regulations were not updated or complex emergency drills were not carried out because of a concern that the public might get the impression that NPPs were not safe, in contrast to the basic assumption [5].

The same basic assumption that NPPs were safe also influenced TEPCO’s actions, giving it confidence in the ability of the technical features of its plants to avoid severe nuclear accidents. This meant that TEPCO was not sufficiently prepared to mitigate the accident of March 2011 [6, 7, 65]. The risk of flooding triggering a nuclear accident was outside the basic assumption, so the latest international guidance on severe accident management was not always followed [66]. The basic assumption also excluded the possibility of a common cause failure which could lead to station blackout for multiple units.

The fact that relevant organizations and their staff did not challenge or re-examine the basic assumptions about nuclear safety illustrates a deficiency in safety culture. As identified in Box 2.9, the third stage of a safety culture programme identifies the need to have a continuing process of improvement, which should include periodic reconsideration of the adequacy of nuclear safety. One means of challenging basic assumptions is to take a systemic approach to nuclear safety and to understand the complexity of the full range of interactions between human, organizational and technical factors. Not sufficiently addressing these interactions was one of the contributory factors to the accident, because the basic assumption remained undetected.

Box 2.10. Basic assumptions [64]

To understand safety culture in its entirety, the artefacts and behaviour, espoused values and basic assumptions that form the three levels of the concept of culture as it applies to safety must be identified. The application of the Three Level model to a specific organization would reflect the uniqueness of that organization and allow logical links to be made between the artefacts, espoused values and basic assumptions. Logical links will not be apparent in the illustrative examples shown below, as they are not derived from any particular organization.

Artefacts are the easiest to observe, but their meaning is the most difficult to interpret. Knowledge of espoused values will help with the meaning, but it is only when the basic assumptions are understood that the meaning of the components at the artefact level will become apparent.

Artefacts and behaviour: Architecture, greeting rituals, dress, forms of address — visible;

Espoused values: Strategies, goals, philosophies — can be elicited;

Basic assumptions: Human nature, basis on which people are respected — unconsciously held and usually tacit.

Basic assumptions lie at the deepest level of culture. They are fundamental beliefs that are so taken for granted that most people in a cultural group subscribe to them, but not in a conscious way. To understand any culture, it is necessary to unearth these basic assumptions that are operating. In the case of an organization, they will also reflect its history, and the values, beliefs and assumptions of the founders and key leaders who have made it successful. Basic assumptions are rarely discussed and confronted and are extremely difficult to change.

Box 2.11. Systemic approach to safety [67]

The systemic approach to safety addresses the whole system by considering the dynamic interactions within and among all relevant factors of the system — individual factors (e.g. knowledge, thoughts, decisions, actions), technical factors (e.g. technology, tools, equipment) and organizational factors (e.g. management system, organizational structure, governance, resources).

The systemic approach to safety works by addressing this complex system of interactions as a whole. For example, among the important factors to consider in these interactions at an NPP are those related to individuals, such as knowledge, decisions, thoughts, emotions and actions. The technical factors include the physical aspects of the NPP and the range of technical tools and equipment used for operation. The organizational factors include the management system, organizational structure, governance of the plant and human and financial resources. Taking into account the interaction between all the individual, technical and organizational factors reveals the complexity and non-linearity of the operations at an NPP. It is necessary to better examine the ways in which the weaknesses and strengths of all these factors influence one another in order proactively to reduce or eliminate risks.

The tendency of the majority of stakeholders not to challenge the adequacy of the existing safety features of the plant strengthened the assumption that the robustness of the plant's technical design and the existing safety measures would be sufficient to protect the plant. This led to necessary safety improvements not being made proactively and promptly [5–7].

The operators who directly responded in the early stages of the accident did so under extreme circumstances. The anxiety and stress associated with their actions were further exacerbated by the fact that they often did not have information about the safety of their families or the condition of their homes. Individuals at the site did not know how the accident would progress, which created significant uncertainty; despite this, they did all they could to protect people and the environment. The situation faced by the operators was unprecedented — managing a multiple unit accident during a national crisis with a heavily damaged infrastructure. This created an extremely adverse working environment from the physical and psychological perspectives.

The interaction of human, organizational and technical factors across all stakeholder organizations and between different levels inside each organization occurs within the broader scope of the safety culture of the organization, and in this way reflects the organization's safety culture. With a systemic approach to safety that analyses the human, organizational and technical factors, an organization can be better prepared for an unexpected event. Nuclear safety will also depend on people's attitudes and behaviour [67]. Human and organizational factors that lead to basic assumptions on safety not being challenged, may result in organizations and individuals taking decisions and performing actions that may inadvertently compromise nuclear safety. It is important to be mindful of such basic assumptions and work to understand their impact on nuclear safety.

2.3. OBSERVATIONS AND LESSONS

A number of observations and lessons have been compiled as a result of the assessment of the nuclear safety considerations of the accident.

— **The assessment of natural hazards needs to be sufficiently conservative. The consideration of mainly historical data in the establishment of the design basis of NPPs is not sufficient to characterize the risks of extreme natural hazards. Even when comprehensive data are available, due to the relatively short observation periods, large uncertainties remain in the prediction of natural hazards.**
  Extreme natural events that have a very low probability of occurrence can result in significant consequences, and the prediction of extreme natural hazards remains difficult and controversial due to the existence of uncertainties. Additionally, such predictions may change during the life of an NPP as more information becomes available and methods of analysis improve. It is therefore necessary to use all relevant available data, both domestic and international, to ensure a reliable prediction of hazards, to define a reliable and realistic design basis against natural extreme events, and to design NPPs with sufficient safety margins.
— **The safety of NPPs needs to be re-evaluated on a periodic basis to consider advances in knowledge, and necessary corrective actions or compensatory measures need to be implemented promptly.**
  The periodic safety review programme at the Fukushima Daiichi NPP did not lead to safety upgrades based on regulatory requirements. TEPCO performed the re-evaluation on a voluntary basis considering advances in knowledge, including new information and data. When faced with a revised estimate of a hazard that exceeds previous predictions, it is important to ensure the safety of the installation by implementing interim corrective actions against the new hazard estimate while the accuracy of the revised value is being evaluated. If the accuracy of a new hazard estimate is confirmed, the operating organization and regulatory authority need to agree on a schedule and comprehensive action plan to promptly address the method of coping with such higher hazards to ensure plant safety.
— **The assessment of natural hazards needs to consider the potential for their occurrence in combination, either simultaneously or sequentially, and their combined effects on an NPP. The assessment of natural hazards also needs to consider their effects on multiple units at an NPP.**

The Fukushima Daiichi accident demonstrated the need to fully investigate the potential for a combination of natural hazards affecting multiple units at an NPP. The complex scenarios resulting from the occurrence of a combination of natural hazards need to be taken into account when considering accident mitigation measures and recovery actions.

— **Operating experience programmes need to include experience from both national and international sources. Safety improvements identified through operating experience programmes need to be implemented promptly. The use of operating experience needs to be evaluated periodically and independently.**

The operating experience evaluation programme at the Fukushima Daiichi NPP did not lead to design changes that took account of domestic or international experience involving flooding. The review of operating experience needs to be a standard part of plant oversight processes, with account taken of relevant sources such as the Incident Reporting System of the IAEA and the OECD Nuclear Energy Agency. Regulatory bodies need to perform independent reviews of national and international operating experience to confirm that operating organizations are taking concrete actions to improve safety.

— **The defence in depth concept remains valid, but implementation of the concept needs to be strengthened at all levels by adequate independence, redundancy, diversity and protection against internal and external hazards. There is a need to focus not only on accident prevention, but also on improving mitigation measures.**

The flooding resulting from the tsunami simultaneously challenged the first three protective levels of defence in depth, resulting in common cause failures of equipment and systems. Even when faced with this situation, operators were able to apply effective, albeit delayed, mitigation strategies. All layers of defence in depth associated with both prevention and mitigation of accidents should be strengthened by adequate independence, redundancy, diversity and protection so that they are not simultaneously challenged by an external or internal hazard and are not prone to common cause failure. The application of the defence in depth concept needs to be periodically re-examined over the lifetime of an NPP to ensure that any change in vulnerability to external events is understood and that appropriate changes to the design are made and implemented. There is a need for extreme external hazards to be addressed in periodic safety reviews, because such hazards can result in common cause failures that may simultaneously jeopardize several levels of defence in depth.

— **Instrumentation and control systems that are necessary during beyond design basis accidents need to remain operable in order to monitor essential plant safety parameters and to facilitate plant operations.**

The loss of instrumentation and control during the accident at the Fukushima Daiichi NPP left operators with little indication of actual plant conditions. The loss of instrumentation and control systems had a serious impact on efforts to prevent a severe accident or to mitigate its consequences. The extent and nature of the necessary instrumentation and control systems need to be defined with care, according to the characteristics of the design of the plant, including spent fuel pools. Systems need to be protected to ensure they are available when needed. This also demonstrated the need to improve strategies to allow for manual control of vital equipment.

— **Robust and reliable cooling systems that can function for both design basis and beyond design basis conditions need to be provided for the removal of residual heat.**

At the Fukushima Daiichi NPP, the operators were eventually, after some delay, able to deploy portable equipment to inject water into the reactors. Cooling systems based either on installed or portable equipment need to be qualified and tested to ensure that they function and can be deployed by operators when needed.

— **There is a need to ensure a reliable confinement function for beyond design basis accidents to prevent significant release of radioactive material to the environment.**

At the Fukushima Daiichi NPP, the failure of venting the containment, and the subsequent failure of the reactor building due to the hydrogen explosion, led to a significant release of radioactive material to the environment. The confinement function needs to be assessed to ensure that all possible hazards are considered in the design of equipment intended to maintain the integrity of the confinement system.

— **Comprehensive probabilistic and deterministic safety analyses need to be performed to confirm the capability of a plant to withstand applicable beyond design basis accidents and to provide a high degree of confidence in the robustness of the plant design.**

Safety analyses can be used both to evaluate and to develop response strategies for beyond design basis accidents and may include the use of both deterministic and probabilistic methods. The probabilistic safety assessment studies conducted for the Fukushima Daiichi NPP were of limited scope and did not consider the possibility of flooding from internal or external sources. The limitations in these studies contributed to the limited scope of accident management procedures available to the operators.

— **Accident management provisions need to be comprehensive, well designed and up to date. They need to be derived on the basis of a comprehensive set of initiating events and plant conditions and also need to provide for accidents that affect several units at a multi-unit plant.**

The accident management procedures available to the operators at the Fukushima Daiichi NPP did not consider the possibility of a multi-unit accident, nor did they provide guidance for the complete loss of electrical power. Accident management provisions need to be based on a plant specific analysis performed by using a combination of deterministic and probabilistic methods. Accident management guidance and procedures need to consider the possibility of events taking place in several units simultaneously and in spent fuel pools. They also need to take into account the possibility of disrupted regional infrastructure, including serious deficiencies in communication, transport and utilities. Accident management provisions should also take into consideration the best available guidance from the international community and be periodically updated to account for new information.

— **Training, exercises and drills need to include postulated severe accident conditions to ensure that operators are as well prepared as possible. They need to include the simulated use of actual equipment that would be deployed in the management of a severe accident.**

Operators at the Fukushima Daiichi NPP had not been specifically trained on how to manually operate systems such as the Unit 1 isolation condenser and fire trucks as an alternative source for low pressure water injection. Special attention is needed in personnel training to perform actions under conditions of prolonged loss of all power, with limited information about the plant status and no information on important safety parameters. Staff training, exercises and drills need to realistically simulate the progression of severe accidents, including the simultaneous occurrence of accidents in several units at the same site. Training, exercises and drills need to involve not only on-site accident management personnel but all off-site responders at the operating organization, local, regional and national levels.

— **In order to ensure effective regulatory oversight of the safety of nuclear installations, it is essential that the regulatory body is independent and possesses legal authority, technical competence and a strong safety culture.**

NISA did not have sufficient authority to take necessary actions, including inspections at regulated facilities. It is essential that the regulatory body is able to make independent decisions on safety over the lifetime of installations. To ensure such independent decision making, the regulatory body must be competent and must possess sufficient human resources, adequate legal authority — including the right to suspend operation and/or to impose improvements in safety on operating organizations — and adequate financial resources. The regulatory body needs the authority to adapt its inspection programme in the light of new safety information. It must also be able to ensure that national regulatory requirements and corresponding guidelines for assessing the safety of nuclear installations are revised periodically in accordance with scientific and technical developments, operational experience, and international standards and practices.

— **In order to promote and strengthen safety culture, individuals and organizations need to continuously challenge or re-examine the prevailing assumptions about nuclear safety and the implications of decisions and actions that could affect nuclear safety.**

This can be achieved by individuals and organizations embracing a questioning attitude to identify the nature, boundaries and potential threats of their shared assumptions about nuclear safety. The institutionalization of a continuous dialogue within organizations, and among different organizations, on issues related to nuclear safety, and their significance and impact on decisions and actions, is essential. Periodic assessments of safety culture can help to foster reflection and dialogue on basic assumptions.

— **A systemic approach to safety needs to consider the interactions between human, organizational and technical factors. This approach needs to be taken through the entire life cycle of nuclear installations.**
  The accident at the Fukushima Daiichi NPP showed that it is difficult to identify vulnerabilities in systems that involve complex interactions between people, organizations and technology because basic assumption regarding nuclear safety can remain undetected. A systemic approach that includes human, technological and organizational considerations is necessary to understand how the components of the overall system function and interact in both normal operation and accident conditions.

3. EMERGENCY PREPAREDNESS AND RESPONSE

This section describes the key events and response actions from the onset of the accident on 11 March 2011. It also considers the national emergency preparedness and response system in place in Japan prior to the accident and the international framework for emergency preparedness and response.

Key international requirements for preparedness to respond to a nuclear emergency which existed prior to the accident are summarized in Box 3.1.

Box 3.1. Key requirements for preparedness to respond to a nuclear emergency in the IAEA safety standards prior to the accident

The IAEA safety standards [68, 69] in force prior to the accident required the following:

(1) Utilizing an all-hazards approach in developing preparedness and response arrangements[63]; (2) developing an emergency classification system on the basis of observable conditions and measurable criteria (emergency action levels) and initiation of predetermined urgent protective actions for the public (in the predefined zones) promptly following the classification of the emergency by the operator; (3) establishing emergency zones for the full range of possible emergencies, including those of low probability; (4) establishing arrangements for the implementation of protective actions within the emergency zones and beyond, as required; (5) setting national criteria for decisions on public protective actions (evacuation, sheltering, iodine thyroid blocking, relocation, restriction of food and drinking water consumption and distribution, public monitoring and decontamination) in terms of doses and measurable quantities (operational intervention levels), taking account of a range of factors (such as financial and social aspects); (6) making arrangements for carrying out radiation monitoring and environmental sampling and assessment in order to identify new hazards promptly and to refine the strategy for response; (7) identifying, at the preparedness stage, special population groups within emergency zones (e.g. disabled persons, hospital patients) for whom specific arrangements need to be made; (8) establishing arrangements for emergency workers, including setting the dose criteria for different types of tasks, designating emergency workers and ensuring their protection, establishing guidance for managing, controlling and recording their doses, and providing specialized protective equipment, procedures and training; (9) planning for the transition from the emergency phase to long term recovery operations and resumption of normal social and economic activities, including clear allocation of responsibilities, sharing and transferring information, assessing consequences, establishing formal processes to decide on withdrawal of restrictions and other arrangements imposed during the emergency, setting relevant principles and criteria and consulting the public; (10) clearly assigning roles, responsibilities and authorities for emergency preparedness and response at all levels as part of emergency plans; (11) establishing organizational relationships and interfaces among operating and response organizations and preparing operational protocols to coordinate the emergency response at all levels; (12) developing and coordinating emergency plans and procedures at all levels on the basis of assessed hazards; (13) preparing for logistical support through provision of tools, instruments, supplies, equipment, communication systems, specific functional facilities and documentation, including planning for operability and usability of these items and facilities under postulated radiological, working and environmental conditions in the emergency response; (14) planning for and conducting of training, drills and exercises; and (15) establishing a quality assurance programme to ensure that all the supplies, equipment, communication systems, facilities and documentation, etc., are kept continuously up to date, available and functional for use in an emergency.

[63] 'Arrangements' — the integrated set of infrastructural elements necessary to provide the capability for performing a specified function or task required in response to a nuclear or radiological emergency. These elements may include authorities and responsibilities, organization, coordination, personnel, plans, procedures, facilities, equipment and training.

The types of protective actions in a nuclear emergency are summarized in Box 3.2.

Box 3.2. Types of protective actions in a nuclear emergency [48, 69]

'**Mitigatory actions'** are immediate actions to reduce the potential for conditions to develop that would result in exposure or a release of radioactive material requiring emergency actions on or off the site, or to mitigate plant conditions that could result in exposure or a release of radioactive material requiring emergency actions on or off the site.

'Urgent protective actions' are actions that must be taken promptly (normally within hours) in order to be effective. The most common urgent protective actions in a nuclear emergency are evacuation, sheltering, iodine thyroid blocking, restriction of the consumption of potentially contaminated food and decontamination of individuals.

'Early protective actions' are those actions that must be taken within days or weeks to be effective. They can be long lasting, even after the termination of the emergency. Unlike urgent protective actions, it is generally possible to base these actions on the results of monitoring that takes account of the specific nature of the release of radioactive material and its dispersion in the environment. Examples of early protective actions include relocation, restrictions on food and drinking water and controls on agriculture.

3.1. INITIAL RESPONSE IN JAPAN TO THE ACCIDENT

At the time of the accident, separate arrangements were in place to respond to nuclear emergencies and natural disasters at the national and local levels. There were no coordinated arrangements for responding to a nuclear emergency and a natural disaster occurring simultaneously.

The arrangements to respond to nuclear emergencies envisaged that, following the detection of relevant adverse conditions at an NPP (e.g. loss of all AC power supplies for more than five minutes or loss of all capabilities to cool the reactor), a notification would be sent from the plant to local and national governments. The national Government would then assess and determine whether the situation was to be categorized as a 'nuclear emergency'[64]. If the situation was categorized as a nuclear emergency, a declaration to that effect would be issued at the national level, and decisions about necessary protective actions would be taken on the basis of dose projections.

Based on a report from the Fukushima Daiichi NPP, the national Government declared a nuclear emergency on the evening of 11 March and issued orders for protective actions for the public. The response at the national level was led by the Prime Minister and senior officials at the Prime Minister's Office in Tokyo.

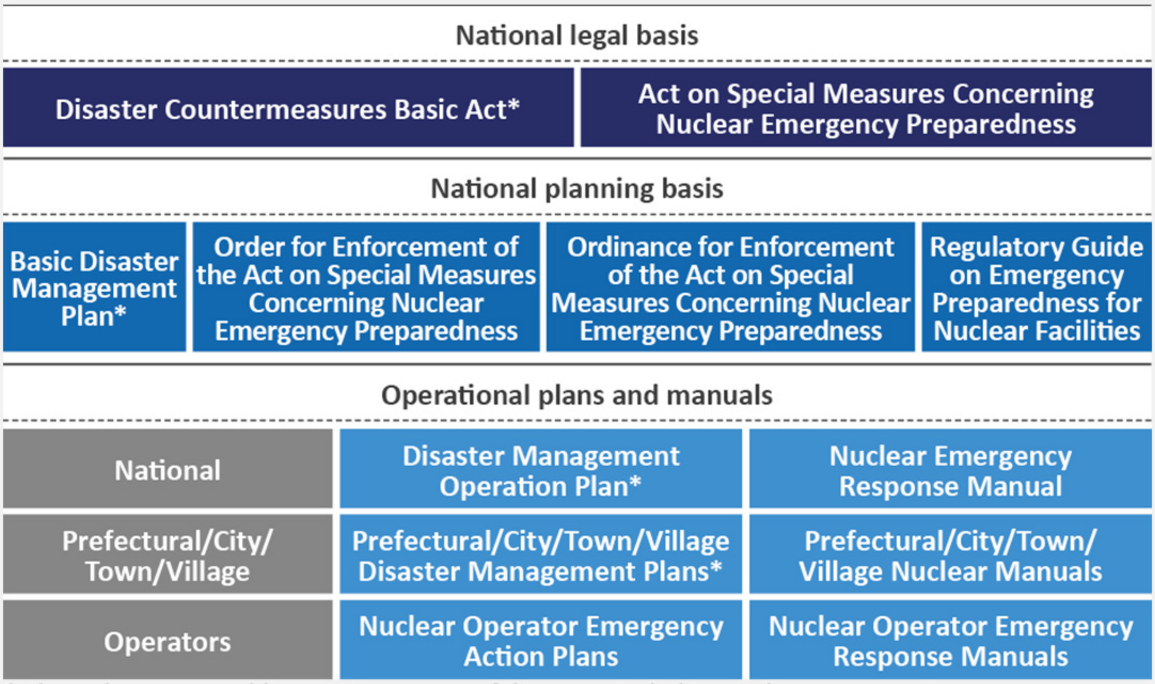
The consequences of the earthquake and tsunami, and increased radiation levels, made the on-site response extremely difficult. The loss of AC and DC electrical power, the presence of a huge amount of rubble that hindered on-site response measures, aftershocks, alerts for further tsunamis and increased radiation levels meant that many mitigatory actions could not be carried out in a timely manner. The national Government was involved in decisions concerning mitigatory action on the site.

[64] Act on Special Measures Concerning Nuclear Emergency Preparedness, Act No. 156 of 1999, as last amended by Act No. 118 of 2006, hereinafter referred to as the Nuclear Emergency Act.

The activation of the emergency Off-site Centre, located 5 km from the Fukushima Daiichi NPP was difficult because of extensive infrastructure damage caused by the earthquake and tsunami. Within a few days, it became necessary to evacuate the Off-site Centre due to adverse radiological conditions.

The primary legal basis for the national emergency preparedness and response system in Japan was set out in the Disaster Countermeasures Basic Act [70] and the Act on Special Measures Concerning Nuclear Emergency Preparedness [19] (Box 3.3).

Box 3.3. Key documents defining the national emergency preparedness and response system for a nuclear emergency in Japan at the time of the accident



** These documents address various types of disasters, including nuclear emergencies*

3.1.1. Notification

Notification from the NPP to local and national governments was required under Article 10 of the Nuclear Emergency Act [19] when certain predefined 'specific events' occurred, such as failure of all AC power supplies for more than five minutes [55]. Under Article 15 of the Nuclear Emergency Act, a report of a 'nuclear emergency' would be sent when certain predefined criteria were met or exceeded, such as the loss of all capabilities to cool the reactor [21, 71].

It was assumed that a report of an event under Article 15 would follow a notification of an event under Article 10 [72]. Notification would trigger an assessment and judgement by the national Government as to whether the event was a 'nuclear emergency'. If this was judged to be the case, the Prime Minister would be briefed and presented with a draft declaration of a 'nuclear emergency'. The

Prime Minister would be responsible for deciding to declare a ‘nuclear emergency’ and issuing orders[65] and/or recommendations for protective actions to the public [73].

Key actions to be taken if an event fell under Article 10 and/or Article 15 of the Nuclear Emergency Act are summarized in Fig. 3.1 [19, 70, 73–75].

The tsunami wave that flooded the Fukushima Daiichi NPP arrived at 15:36 on 11 March 2011 [10]. Notification by the plant of a ‘specific event’ for Units 1 to 5 under Article 10 of the Nuclear Emergency Act [19] was sent to national and local governments at 15:42 on 11 March, followed at 16:45 by a report of an event at Units 1 and 2 classified as a ‘nuclear emergency’ under Article 15 of the Act [3, 8, 76, 77].

The type of the ‘specific event’ reported under Article 10 was a ‘station blackout’ for Units 1–5 [76]. The type of the event reported as a ‘nuclear emergency’ under Article 15 was initially the “inability of water injection of the emergency core cooling system” for Units 1 and 2 [77]. After receiving notification, the national Government assessed the situation and made a judgement that the situation was a ‘nuclear emergency’ [6].

The Prime Minister issued a declaration of a nuclear emergency at 19:03. This was more than two hours after having been notified by the Fukushima Daiichi NPP of an event at Units 1 and 2 classified as a ‘nuclear emergency’ under Article 15 of the Act, following lengthy discussions among off-site officials [3].

3.1.2. Mitigatory actions

An emergency response centre, headed by the Site Superintendent, was established at the Fukushima Daiichi NPP, in accordance with TEPCO’s Disaster Response Manual, around 15 minutes after the earthquake [6, 8]. It was located in the seismically isolated building, which was fitted with special features including an autonomous electrical power supply and ventilation systems with filtration devices. This building had been constructed[66] as a result of lessons learned from the experience of the Kashiwazaki-Kariwa NPP following the Niigata-Chuetsu-Oki earthquake in 2007, and its use enabled mitigatory actions to continue at the site during the response to the accident [8].

The arrangements that existed prior to the accident envisaged that, in case of need, the on-site emergency response centre would send a request for support to TEPCO Headquarters, using TEPCO’s capabilities or resources gathered from other nuclear operating organizations, through the Agreement on Cooperation between Japanese Nuclear Operators [8, 75].

Following a request from the Fukushima Daiichi NPP, additional staff and equipment from other Japanese NPPs (not operated by TEPCO) were mobilized to support the on-site emergency response. However, extensive damage caused to the transport infrastructure by the earthquake and tsunami, in addition to insufficient pre-planning, impaired the effectiveness of this support. For example, in cases where the request for equipment did not contain an adequate specification of what was required, it led to the procurement of equipment that was incompatible with existing plant equipment (due to mismatched fittings, connectors, etc.) [8].

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[65] The Nuclear Emergency Act [19] and the Disaster Countermeasures Basic Act [70] use the terms ‘instructions’ and ‘recommendations’ for issuing protective actions. An ‘instruction’ is mandatory and the public is therefore required to adhere to it. A ‘recommendation’ is only a suggestion and therefore not mandatory. However, for the purposes of clarity, the term ‘orders’ is used in this report as an equivalent of ‘instructions’.

[66] The construction started in March 2009 and the building was put into operation in July 2010.

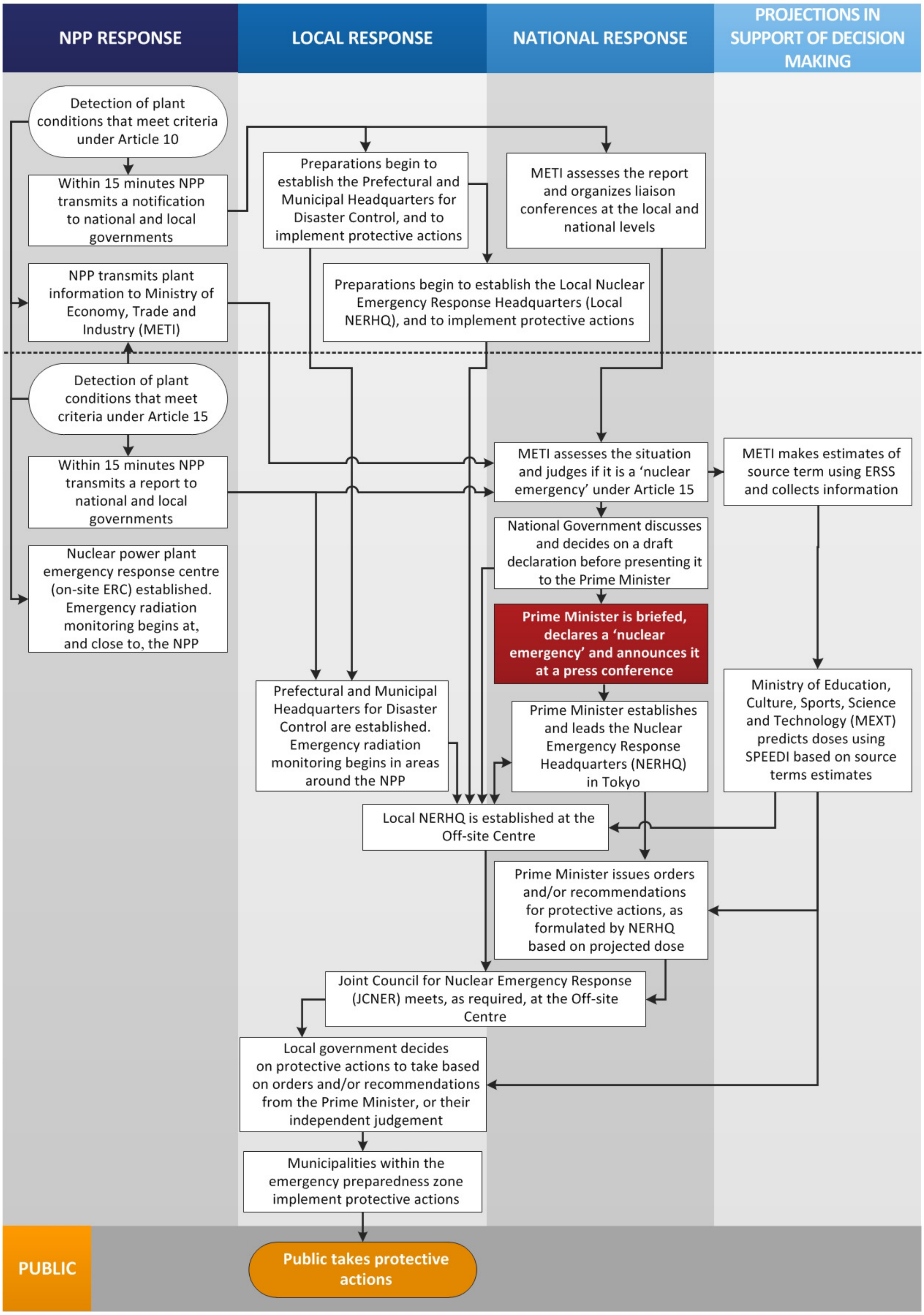

FIG. 3.1. Key actions if an event falls under Article 10 and/or Article 15 of the Nuclear Emergency Act, as planned prior to the accident (based on Refs [19, 70, 73–75]).

In response to the emergency, personnel from TEPCO, from contractors and from other Japanese NPPs (not operated by TEPCO) were dispatched to the site to assist with various tasks, including restoring power and monitoring instruments, injecting cooling water into reactors, removing rubble and monitoring radiation levels [8]. Personnel from national Government agencies and organizations — such as the Japan Self-Defense Force, police and firefighters — were also dispatched to the site. They helped with activities including operating the large equipment needed to pour or spray water onto the spent fuel pools in Units 1, 3 and 4, and providing helicopter surveillance of the spent fuel pools [3, 6, 8].

The earthquake and tsunami resulted in the loss of AC and DC electrical power and a huge amount of rubble. There were also aftershocks and alerts of possible further tsunamis. As a result of these factors, as well as increased radiation levels and the hydrogen explosions, and also due to the lack of detailed arrangements, the response was extremely difficult and many mitigatory actions could not be carried out in a timely manner [8]. Workers at the site carried out mitigatory actions under very difficult conditions; they worked longer hours and under far more tiring circumstances than would normally be expected [8].

The national Government was involved in decisions concerning mitigatory actions, such as the injection of sea water for fuel cooling [6, 7]. Roles, responsibilities and authorities in this regard had not been clearly assigned at the preparedness stage.

3.1.3. Management of the emergency

The national emergency preparedness and response system in place at the time of the accident envisaged that the core entities in managing the nuclear emergency would be the Nuclear Emergency Response Headquarters (NERHQ)[67] and its Secretariat[68], as well as the Local Nuclear Emergency Response Headquarters (Local NERHQ)[69]. The NERHQ would direct and coordinate the national response, which was to include preparing and issuing orders and/or recommendations on evacuation to the local government [19].

For a national response at the local level, the overall management of the response to a nuclear emergency was to be coordinated, as soon as possible, by the Local NERHQ at the Off-site Centre, located 5 km from the Fukushima Daiichi NPP. The Prefectural Nuclear Emergency Response Headquarters (Prefectural NERHQ) and the Joint Council for Nuclear Emergency Response (JCNER) were also planned to be located in the Off-site Centre [73, 74, 78].

For the prefectural response to a nuclear emergency, it was planned that the Prefectural NERHQ and the Fukushima Prefecture Headquarters for Disaster Control would coordinate activities at the prefectural level. The JCNER would coordinate between the national response at the local level and the prefectural response [19, 73, 74].

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[67] The NERHQ was to be composed of those appointed by the Prime Minister from among the officials of the Cabinet Secretariat and designated administrative organs [19]. The Prime Minister was to serve as the Director General of the NERHQ, which was planned to be located in the Prime Minister's Office (see Fig. 3.2).

[68] The Secretariat was to be staffed by representatives of key organizations and headed by the Director General of the Nuclear and Industrial Safety Agency (NISA), which was part of the Ministry of Economy, Trade and Industry (METI). It was planned to be located in the METI/NISA emergency response centre in the METI building (see Fig. 3.2).

[69] The Local NERHQ was to be staffed with individuals from all relevant organizations, with the METI Senior Vice Minister as Director General. It was planned to be located at the Off-site Centre (see Fig. 3.2).

Separate arrangements were in place to respond to nuclear emergencies and natural disasters at the national and local levels. These arrangements did not envisage the need to respond to a nuclear emergency and a natural disaster occurring simultaneously [74, 78].

The locations of the core entities in the management of the response to a nuclear emergency as planned prior to the accident are shown in Fig. 3.2.

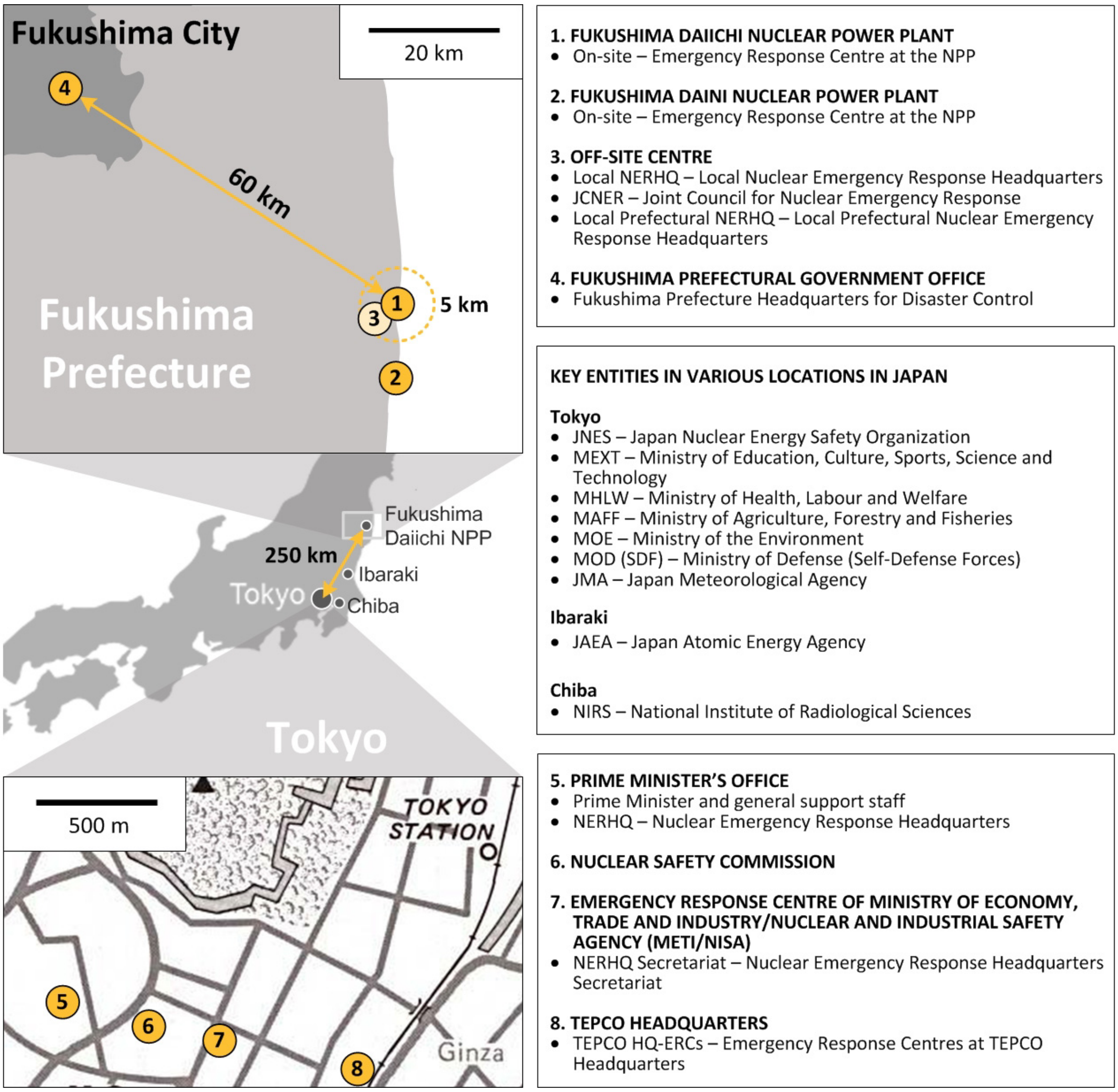

FIG. 3.2. Locations of the core entities involved in management of the response to a nuclear emergency[70].

At 14:50 on 11 March 2011, an Emergency Response Office for dealing with the earthquake was established in the Prime Minister's Office by the Deputy Chief Cabinet Secretary for Crisis Management. At 15:14, the national Government established the Emergency Disaster Response Headquarters in the Prime Minister's Office in Tokyo, with the Prime Minister as the Headquarters'

[70] Based on Refs [7, 8, 73, 74, 79–91].

Director General. At 16:36, the Deputy Chief Cabinet Secretary for Crisis Management established an Emergency Response Office for the nuclear accident at the Prime Minister's Office [6].

At 19:03 on 11 March 2011, the national Government established the Nuclear Emergency Response Headquarters, at the same time as the declaration of a nuclear emergency was issued [3].

As the accident evolved so fast, there was no time for detailed discussions during meetings of the NERHQ. The core group for the emergency response became the Prime Minister and senior officials, located at the Prime Minister's Office. The Prime Minister issued evacuation orders to local governments without the involvement of the Secretariat of the NERHQ [7].

The Government–TEPCO Integrated Response Office — an integrated headquarters of the operating organization and the Government response organization — was established on 15 March 2011 at TEPCO Headquarters in Tokyo [6] to ensure the timely sharing of information at the national level.

At the local level, the extensive damage caused by the earthquake and tsunami led to difficulties in initiating operations in the Off-site Centre [92]. As a result, the Local NERHQ and other entities, which were supposed to operate from the Off-site Centre (JCNER and Prefectural NERHQ), could not fulfil their roles. On 15 March 2011, it became necessary to evacuate the Off-site Centre, due to the worsening radiological conditions[71], and to relocate to the Fukushima Prefectural Public Hall, located approximately 60 km from the Fukushima Daiichi NPP [6, 92]. This facility did not have capabilities equivalent to those of the Off-site Centre, which led to difficulties, for example, in sharing information in real time among the relevant authorities.

For the prefectural response, a new 'nuclear squad'[72] was formed in the Fukushima Prefecture Headquarters for Disaster Control, as part of the structure set up to respond to the earthquake and tsunami, to coordinate activities at the prefectural level [7].

3.2. PROTECTING EMERGENCY WORKERS

At the time of the accident, the national legislation and guidance in Japan addressed measures to be taken for the protection of emergency workers[73], but only in general terms and not in sufficient detail.

Many emergency workers from different professions were needed to support the emergency response. Emergency workers came from various organizations and public services. However, there were no arrangements in place to integrate into the response those emergency workers who had not been designated prior to the accident.

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[71] The Off-site Centre had not been designed to withstand the increasing radiation levels.

[72] A new nuclear squad was formed because the existing nine functional squads, as specified in the Fukushima Prefecture Disaster Management Plan [74], were engaged in response to the earthquake and tsunami [7].

[73] The IAEA uses the term 'emergency workers' to cover those with specified duties as a worker (any person who works, whether full time, part time or temporarily, for an employer and who has recognized rights and duties in relation to occupational radiation protection) in response to an emergency, including workers employed, both directly and indirectly, by registrants and licensees as well as personnel of responding organizations, such as police officers, firefighters, medical personnel, and drivers and crews of evacuation vehicles. In Japan, the term 'emergency preparedness personnel' is used to cover all those who perform emergency response activities in a nuclear emergency, such as "communication of public information and instructions to residents in the vicinity, guidance of residents in the vicinity for evacuation, traffic control, radiation monitoring, medical treatment provision, and actions to prevent a situation from developing into a disaster in a nuclear facility, and those who perform disaster recovery activities such as removal of radioactive contaminants" [93].

Implementation of the arrangements for ensuring the protection of workers against radiation exposure was severely affected by the extreme conditions at the site. In order to maintain an acceptable level of protection for on-site emergency workers, a range of impromptu measures was implemented. The dose limit for emergency workers undertaking specific tasks was temporarily increased to allow the necessary mitigatory actions to continue. Medical management of emergency workers was also severely affected and major efforts were required to meet the needs of on-site emergency workers.

Members of the public, referred to as 'helpers', volunteered to assist in the off-site emergency response. National authorities issued guidance on the type of activities that helpers could carry out and on measures to be taken for their protection.

3.2.1. Protection of personnel at the plant following the earthquake and tsunami

Following the tsunami alert, efforts were made to protect plant personnel (about 6000 people) from the expected impact of the tsunami. Tsunami alerts were broadcast using the on-site public address system, advising personnel to evacuate and to relocate to designated locations at higher levels. While in most cases these efforts were successful, not all personnel received the tsunami alert and evacuation orders [7, 8]. Two workers who were checking equipment after the earthquake on the underground floor of the Unit 4 turbine building were drowned in the flooding caused by the tsunami [8].

The protection of plant personnel from the effects of the tsunami was successful largely due to lessons learned from the experience at the Kashiwazaki-Kariwa NPP following the Niigata-Chuetsu-Oki earthquake in 2007, and efforts made afterwards in developing procedures for emergency exit [8].

From 11 to 14 March 2011, plant personnel not considered essential — including female workers and most of the employees of subcontractors — were evacuated from the site. On the morning of 15 March, an evacuation of additional plant personnel took place because of worsening conditions at the site. An estimated 50–70 staff remained at the site, while approximately 650 people were temporarily evacuated to the Fukushima Daini NPP using buses or private vehicles. They began to return to the Fukushima Daiichi NPP from noon on the same day [8].

3.2.2. Protective measures for emergency workers

The national legislation and guidance in Japan at the time of the accident addressed measures to be taken for the protection of emergency workers. However, the arrangements that were in place, such as the on-site plan, addressed these requirements only in a general way and not in sufficient detail. For example, the on-site plan covered the following areas: defining responsibilities; assigning generic duties in emergency preparedness and response; and listing an inventory of available instrumentation (e.g. survey meters and electronic dosimeters) [75].

Dose limits for emergency workers were set depending on their intended tasks, with an upper dose limit of 100 mSv for life saving actions and activities to prevent the development of catastrophic conditions, while efforts to minimize the exposure were required [93, 94].

During the accident, a range of impromptu measures were adopted to maintain an acceptable level of protection for on-site emergency workers under the extreme conditions. There was a lack of personal dosimeters, as most of those at the site had become inoperable after the tsunami. This made it necessary to take contingency measures to track the individual doses received by the on-site emergency workers [8]. For example, an instruction was issued to use a single electronic personal dosimeter per group of emergency workers expected to work in similar conditions. For emergency workers in the seismically isolated building, doses were measured and controlled by area dose rate monitoring and by the amount of time spent by workers in the specific areas. This situation continued until the end of March 2011, by which time a sufficient number of dosimeters had been received from other NPPs [6, 8].

On 14 March 2011, the dose limit for emergency workers undertaking specific emergency work was temporarily increased to 250 mSv to allow the necessary activities to continue on-site and within a 30 km radius of the Fukushima Daiichi NPP [95]. A dose of 100 mSv remained the limit for emergency workers from the firefighting service for life-saving actions [6]. The temporary increase in the dose limit to 250 mSv was withdrawn on 1 November 2011 for on-site emergency workers who began working from this date onwards; on 16 December 2011 it was withdrawn for the majority of the remaining emergency workers; and on 30 April 2012 it was withdrawn for a small group of emergency workers with specialized knowledge and experience [96, 97].

Most on-site emergency workers received doses below 250 mSv [8]. There were six cases in which emergency workers incurred doses in excess of the dose criterion of 250 mSv, with the highest dose of 678 mSv (of which 590 mSv was due to internal contamination).

Internal contamination was attributed to the severe working conditions and the inadequate implementation of protective measures (e.g. improper use of respiratory protection, iodine thyroid blocking measures, actions that resulted in inadvertent ingestion of radionuclides), due primarily to the lack, or ineffectiveness, of training [5].

TEPCO also faced challenges in ensuring the well-being of on-site emergency workers, for example in providing adequate facilities and conditions (for resting, sleeping, eating, sanitation, etc.) [98–101].

During the response to the accident, people from the affected areas, as well as from all over Japan, including from a number of non-governmental organizations, referred to as ‘helpers’, volunteered to assist in activities such as the provision of food, water and necessities, and later in decontamination and monitoring activities. National authorities issued guidance on the type of activities helpers could carry out and on measures to be taken for their protection [102–104].

3.2.3. Designation of emergency workers

Many different types of emergency workers were needed to support the on-site and off-site emergency response. On-site emergency workers included NPP personnel, either directly employed by TEPCO or subcontracted, as well as personnel from the Japan Self-Defense Force, the firefighting services and police engaged in emergency work on the site [8]. Off-site emergency workers included personnel from different organizations and services (governmental and non-governmental). Their tasks included evacuation of the public and of special facilities, offering support to evacuees, providing medical care and carrying out monitoring and sampling [6, 97, 105, 106].

Not all of the emergency workers had been designated as such prior to the emergency (e.g. some TEPCO employees and employees of subcontractors), and arrangements were not in place to integrate them into the response after their designation as emergency workers. Additionally, many of those who had not been designated prior to the emergency had not been trained to work in conditions of a nuclear emergency. For example, they had not been trained in radiation protection aspects, informed of the potential health risks from radiation exposure, or trained in the use of respiratory protection or in dealing with patients potentially contaminated with radioactive material [107]. This resulted in some delay in implementation of mitigatory actions early in the response [6].

3.2.4. Medical management of emergency workers

Obtaining the necessary medical treatment for emergency workers with conventional injuries was difficult because several hospitals were closed as a result of the evacuation or sheltering, and some were not prepared to treat patients possibly contaminated with radioactive material [107, 108]. Until primary medical care was provided on the site, emergency workers with conventional injuries were transported to one of two local hospitals for treatment [108].

About 17 hours after the earthquake, the NIRS dispatched a Radiation Emergency Medical Assistance Team (REMAT), consisting initially of a physician, a nurse and a health physicist, to the Local NERHQ (in the Off-site Centre) to perform assessments of the contamination and decontamination for emergency workers [107].

Occupational health doctors began to provide primary care for on-site emergency workers at the emergency response centre in the seismically isolated building eight days after the beginning of the accident. Two triage centres were subsequently established, one on-site and the other in 'J-Village'[74] [3, 8, 108].

From 1 July 2011, an emergency care facility was established at the Fukushima Daiichi NPP. For this facility, medical staff trained to deal with radiation emergencies were recruited from all over Japan [8, 108].

3.3. PROTECTING THE PUBLIC

National emergency arrangements at the time of the accident envisaged that decisions on protective actions would be based on estimates of the projected dose to the public that would be calculated when a decision was necessary using a dose projection model — the System for Prediction of Environmental Emergency Dose Information (SPEEDI). The arrangements did not envisage that decisions on urgent protective actions for the public would be based on predefined specific plant conditions. However, in response to the accident, the initial decisions on protective actions were made on the basis of plant conditions. Estimates of the source term could not be provided as an input to SPEEDI owing to the loss of on-site power.

The arrangements prior to the accident included criteria for sheltering, evacuation and iodine thyroid blocking in terms of projected dose, but not in terms of measurable quantities. There were no criteria for relocation.

Protective actions for the public implemented during the accident included: evacuation; sheltering; iodine thyroid blocking (through the administration of stable iodine); restrictions on the consumption of food and drinking water; relocation; and the provision of information.

The evacuation of people from the vicinity of the Fukushima Daiichi NPP began in the evening of 11 March 2011, with the evacuation zone gradually extended from a radius of 2 km of the plant to 3 km and then to 10 km. By the evening of 12 March it had been extended to 20 km. Similarly, the area in which people were ordered to shelter was extended from within 3–10 km of the plant shortly after the accident to within 20–30 km by 15 March. In the area within a 20–30 km radius of the NPP, the public was ordered to shelter until 25 March, when the national Government

[74] J-Village is located about 20 km south of the Fukushima Daiichi NPP. Prior to the accident, it was a football training facility. After the accident, it was utilized as a general logistical support base, e.g. for preparing workers for assigned tasks, for their monitoring and decontamination, as necessary, after completion of the assigned tasks, for triage, etc. [3].

recommended voluntary evacuation. Administration of stable iodine for iodine thyroid blocking was not implemented uniformly, primarily due to the lack of detailed arrangements.

There were difficulties in evacuation due to the damage caused by the earthquake and tsunami and the resulting communication and transportation problems. There were also significant difficulties encountered when evacuating patients from hospitals and nursing homes within the 20 km evacuation zone.

On 22 April, the existing 20 km evacuation zone was established as a 'Restricted Area', with controlled re-entry. A 'Deliberate Evacuation Area' was also established beyond the 'Restricted Area' in locations where the specific dose criteria for relocation might be exceeded.

Once radionuclides were detected in the environment, arrangements were made regarding agricultural protective actions in the agricultural area and restrictions on the consumption and distribution of food and consumption of drinking water. In addition, a certification system for food and other products intended for export was established.

Several channels were used to keep the public informed and to respond to people's concerns during the emergency, including television, radio, the Internet and telephone hotlines. Feedback from the public received via hotlines and counselling services identified the need for easily understandable information and supporting material.

3.3.1. Urgent protective actions and relocation

Prior to the accident, 10 km emergency planning zones, in which emergency preparedness was to be significantly enhanced, had been established around the Fukushima Daiichi and Fukushima Daini plant sites (Fig. 3.3). There were plans to implement protective actions within these zones [74].

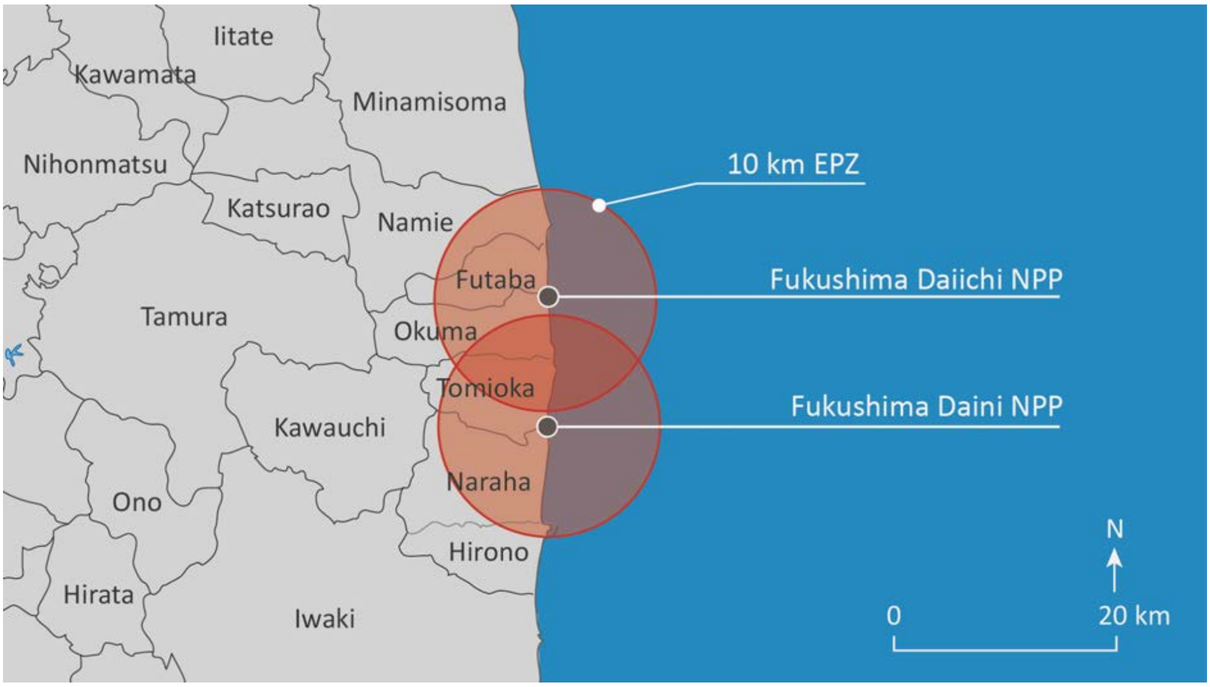

FIG. 3.3. Emergency planning zones (EPZs) for the Fukushima Daiichi and Fukushima Daini NPPs established prior to the accident (based on Ref. [74]).

The emergency response plans envisaged that decisions on protective actions would be based on dose projections performed at the time when a decision was necessary. Doses were to be projected by SPEEDI after the onset of the accident and to be compared with predetermined dose criteria to determine what protective actions were needed and where [73, 93]. This approach was not in line with IAEA safety standards, where the initial decisions on urgent protective actions for the public need to be based on plant conditions [68, 69].

Predetermined dose criteria were available for sheltering[75], evacuation[76] and iodine thyroid blocking[77] in terms of projected dose, but not in terms of measurable quantities. There were no predetermined criteria (i.e. generic, in terms of dose, or operational, in terms of measurable quantities) for relocation[78] [93].

During the response to the accident, 'source term' estimates from the Emergency Response Support System (ERSS) could not be provided as an input to SPEEDI[79] owing to the loss of on-site power. Decisions on evacuation and sheltering were taken on the basis of plant conditions (i.e. loss of core cooling) rather than on dose projections as was planned [3, 7].

The decisions of the national and local governments on protective actions were not always coordinated, mainly as a result of the severe communication problems and partly due to the difficulties in activating the Off-site Centre [92]. At 20:50 on 11 March 2011, Fukushima Prefecture issued an evacuation order for residents within a radius of 2 km of the Fukushima Daiichi NPP on the basis of information received directly from TEPCO [3, 6, 7, 70].

At 21:23, the national Government issued an evacuation order for an area within a radius of 3 km of the plant, and sheltering for an area within a radius of 3–10 km. At 05:44 on 12 March 2011, the national Government issued an order for the evacuation of an area with a radius of 3–10 km, and at 18:25 it was extended to an area within a radius of 20 km of the plant[80] [3, 7].

The communication of evacuation orders to the public was arranged by using the local disaster management radio communication network, sound trucks, police cars and door-to-door visits. As a result of the plant conditions, difficulties in coordination and insufficient pre-planning, orders for evacuation and sheltering were modified several times within 24 hours, and eventually a zone with a radius of 20 km was ordered to evacuate, involving about 78 000 people [7].

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[75] 'Sheltering' is the short term use of a structure for protection from an airborne plume and/or deposited radioactive material [48].

[76] 'Evacuation' is the rapid, temporary removal of people from an area to avoid or reduce short term radiation exposure in an emergency. Evacuation may be performed as a precautionary action based on plant conditions [48].

[77] 'Iodine thyroid blocking' is an urgent protective action to be taken in an emergency involving radioactive iodine. Iodine thyroid blocking involves the administration of a compound of stable iodine (usually potassium iodide) to prevent or reduce the uptake of radioactive isotopes of iodine by the thyroid gland [48].

[78] 'Relocation' is the non-urgent removal of people to avoid longer term exposure (e.g. within one year) from deposited radioactive material [48].

[79] Some projections of doses were performed using other assumptions; however, these projections were not used as a basis for deciding on urgent protective actions [4, 7].

[80] For the Fukushima Daini NPP, an evacuation order to citizens within a radius of 3 km and an order for sheltering within a 3–10 km radius of the plant was issued at 07:45 on 12 March 2011 [6]. Following the hydrogen explosion in Unit 1 of the Fukushima Daiichi NPP (at 15:36 on 12 March), a decision was made at 17:39 on 12 March to evacuate citizens from a 10 km radius around the Fukushima Daini NPP as a precaution in case of a similar hydrogen explosion at this plant [6]. As this 10 km evacuation zone was within the 20 km evacuation zone around the Fukushima Daiichi NPP, no further protective actions were needed in relation to the Fukushima Daini NPP.

There were difficulties in evacuation due to infrastructure damage and communication and transportation problems resulting from the earthquake and tsunami. Significant challenges were also encountered in evacuating patients from hospitals and nursing homes within the 20 km evacuation zone (e.g. providing appropriate transport and evacuation shelters with medical supplies). In spite of damaged roads and traffic jams, most residents not requiring medical support began to leave the evacuation area within a few hours after the orders for evacuation had been issued [7].

The order for the sheltering of residents living within a radius of 20–30 km area around the Fukushima Daiichi NPP was given on 15 March and remained in force until 25 March [3, 7]. This extended time of sheltering and the breakdown of the local infrastructure resulted in serious disruptions to people's lives [7]. On 25 March 2011, a recommendation for voluntary evacuation was issued by the national Government to residents within the 20–30 km zone [3, 7]. Many residents, however, had already voluntarily left the area.

Administration of stable iodine for iodine thyroid blocking was not implemented uniformly, owing primarily to inadequate pre-planned arrangements. Some local governments distributed stable iodine tablets but did not advise taking them, while others distributed the tablets and advised the public to take them, and still others awaited instructions from the national Government [6].

Some residents returned to their homes in the evacuated areas to collect belongings before full access controls were established by the end of March 2011 [6]. On 22 April, the existing 20 km evacuation zone around the Fukushima Daiichi NPP was established as a 'Restricted Area', with controlled re-entry and conditions for temporary access, based on consultation with the local governments. In May 2011, short term temporary access was granted, with arrangements in place, including specific instructions and monitoring for contamination [6, 104, 109].

Monitoring of evacuees at the local level began on 12 March 2011. Decisions on the need for decontamination were based on operational criteria established prior to the accident. After several days, these criteria were increased to address existing conditions (e.g. low temperatures, insufficient water supplies) [5].

Environmental monitoring following the accident was performed in difficult and hazardous conditions and with limited equipment and staff. For example, the earthquake and tsunami disabled most of the existing local monitoring equipment. Monitoring within a radius of 20 km of the Fukushima Daiichi NPP began on 12 March and ended on 14 March, when evacuation within this area had been completed. In some locations beyond the 20 km evacuation zone, dose rates of the order of a few hundred microsieverts per hour (μSv/h) were measured from 15 March onward [3, 6].

On 11 April 2011, the national Government announced that the criterion of 20 mSv dose projected to be received within one year from the date of the accident would be used to determine areas beyond the 20 km evacuation zone from which people might need to be relocated[81] [3]. On 22 April 2011, a 'Deliberate Evacuation Area' was established beyond the 20 km evacuation zone to include areas where this projected dose criterion of 20 mSv might be exceeded. The national Government issued an order that relocation of people from this area should be implemented in approximately one month [3].

In addition to the 'Deliberate Evacuation Area', an 'Evacuation Prepared Area in Case of Emergency' was also established on 22 April 2011 (see Fig. 3.4). Residents of the 'Evacuation Prepared Area in Case of Emergency' were advised to shelter or evacuate by their own means in the event of possible

[81] Most of the official Japanese documents describing the response to the Fukushima Daiichi accident do not use the term 'relocation', but refer to the movement of people as 'evacuation'.

renewed concerns regarding the Fukushima Daiichi NPP. The designation of the ‘Evacuation Prepared Area’ was lifted on 30 September 2011 [6].

As a result of the monitoring conducted beyond the ‘Restricted Area’ (i.e. the 20 km evacuation zone) and the ‘Deliberate Evacuation Area’, specific locations were identified with projected doses to residents above 20 mSv within one year after the occurrence of the accident. On 16 June, the national Government announced a guideline which specified that these locations should be designated as ‘Specific Spots Recommended for Evacuation’. Beginning on 30 June, the national Government began to designate these locations to be relocated [6, 7].

The areas and locations for which protective actions were ordered or recommended until 30 September 2011 are shown in Fig. 3.4.

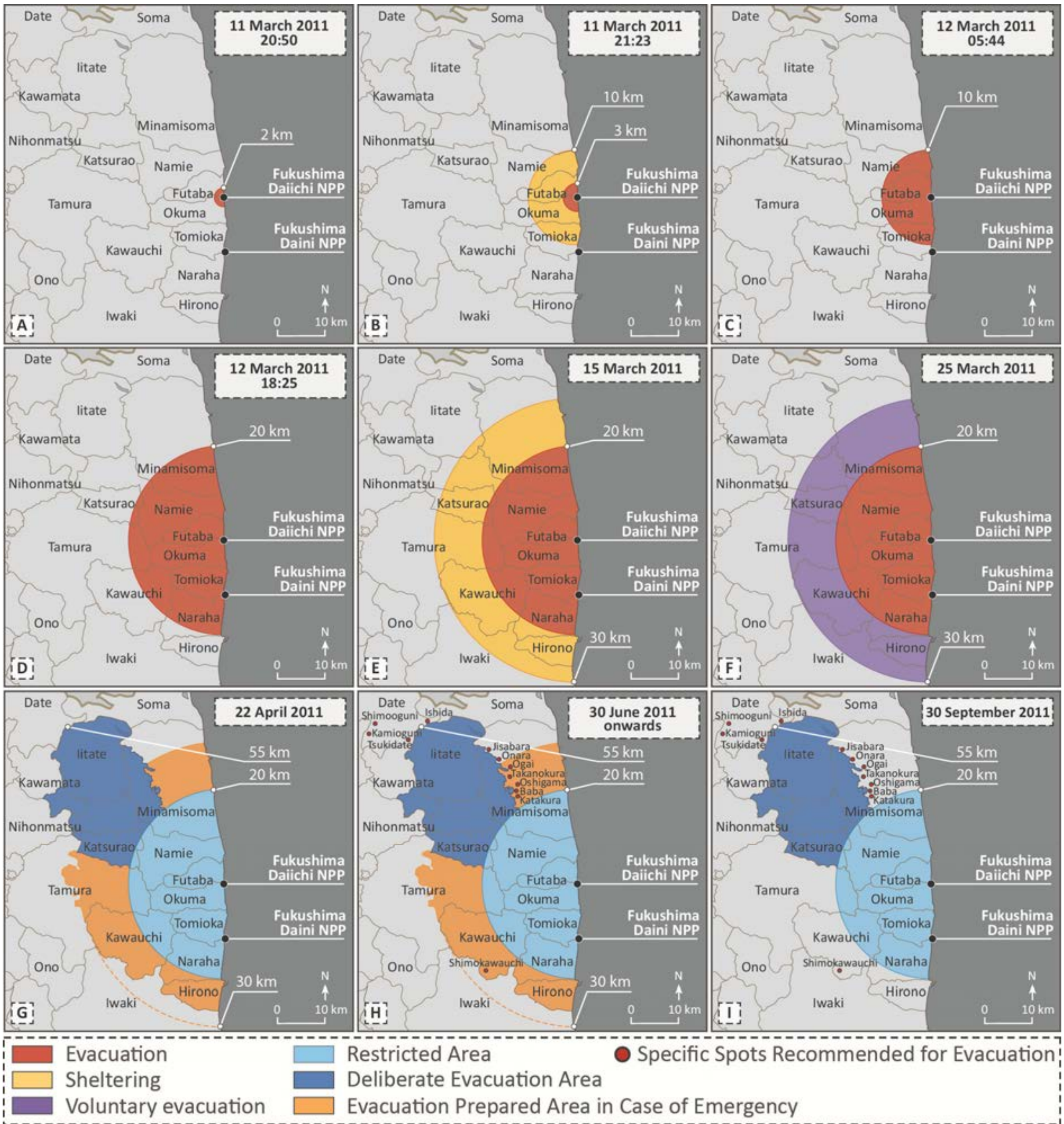

FIG. 3.4. Areas and locations where protective actions were ordered or recommended until 30 September 2011 (based on Refs [3, 6, 7, 104]).

Local government officials had also to decide at an early stage whether to reopen schools and under what conditions. Initially, on 19 April 2011, a dose criterion of 20 mSv/year was established for this purpose. On 27 May, in response to concerns on the part of the public, a notification was issued by the Government of Japan stating the objective to reduce the dose to 1 mSv/year in the near term [7].

3.3.2. Protective actions relating to food, drinking water and agriculture

The criteria of activity concentrations of specific radionuclides to be used in the case of a nuclear emergency for restrictions on food and drinking water produced in Japan had been developed before the accident [93]. However, these values had not been adopted for use in an emergency as specific regulatory limits[82] [6, 7]. On 17 March 2011, these criteria were established as provisional regulation values for radionuclide levels in food and drinking water under the Food Sanitation Act [110].

Following the detection of radioactive material in the environment, arrangements were made for controlling food and drinking water. These arrangements included: (1) radionuclide concentration levels of radioactive caesium and radioactive iodine in food and drinking water established as provisional regulation values under the Food Sanitation Act, above which food and drinking water were restricted; and (2) measurements of radionuclide concentrations in samples of food and drinking water. Within a few weeks, the levels of radioactive iodine (^{131}I) had decreased significantly owing to its short half-life (about 8 days), and the food restrictions in the medium to long term were based on concentrations of radioactive caesium only [110].

On 21 March 2011, the national Government began to issue restrictions on the distribution of specific food [111] that evolved with the changing situation. Food restrictions were formulated on the basis of the results of monitoring of food samples that determined which foods were exceeding the criteria and defined the geographical location(s) affected [112, 113].

A number of challenges with regard to protective actions related to food and drinks were encountered, including: (1) defining the criteria (activity concentrations of radionuclides) that could be used as the basis for food control; (2) determining which foods, in different geographical locations, were or could be affected with levels above these criteria; (3) dealing with the insufficient infrastructure and resources for sampling and analysis; and (4) addressing the concerns of some local governments about performing the sampling and analyses.

On 4 April 2011, a policy was established that enabled placement of food restrictions not only in areas defined by prefectural boundaries but also in smaller geographical areas (such as cities, towns and villages), as appropriate. The policy set out a process to establish or lift restrictions on different food products. Prefectures could apply for modifications to restrictions, on the condition that the food monitoring results were below provisional regulation values three consecutive times in weekly monitoring tests [7].

On 5 April 2011, based on measured concentrations of ^{131}I in fish samples, the provisional regulation values were added for activity concentrations of radioactive iodine in fishery products [114].

On 8 April 2011, a policy was issued on restrictions of rice cultivation in agricultural soil that had radioactive caesium levels in excess of established criteria [6].

[82] Criteria for food imported into Japan (370 Bq/kg of radioactive caesium — ^{134}Cs and ^{137}Cs) were established as regulatory limits following the accident at the Chernobyl NPP in the former Soviet Union in 1986 [7].

On 14 April 2011, radionuclide concentration levels of radioactive caesium and radioactive iodine in animal feed were established as provisional permissible values. Despite the restrictions on animal feed, some beef samples exceeded the provisional regulation values (in July 2011). A control regime was put in place to prevent such meat from being distributed to consumers [6].

On 1 April 2012, standard limits came into force which replaced the provisional regulation values. These limits specified activity concentrations for radionuclides in food and drinking water on the basis of an effective dose of 1 mSv/year (while the criterion of 5 mSv/year had been used as a basis for the provisional regulation values), and taking account of the contributions to dose of a range of radionuclides released during the accident. As a consequence, these values were much lower than the provisional regulation values that they replaced [115].

3.3.3. Public information

Arrangements for informing the public were in place prior to the accident. At the national level, arrangements existed that recognized the need for relevant response organizations to coordinate the provision of information to the public, including the content, timing and method of announcements [73]. The Fukushima Prefecture Disaster Management Plan also included arrangements for public information [74].

The regulatory body, NISA, released its initial message on the impact of the earthquake on nuclear facilities via ‘Mobile NISA’ at 15:16 on 11 March 2011, 30 minutes after the earthquake. The declaration of a nuclear emergency was issued by the Prime Minister at 19:03 and announced at a press conference at 19:45. This was followed by a Government press conference on evacuation orders at 21:52 [6, 7].

The national Government, NISA, local emergency response organizations, local governments and TEPCO held independent press conferences which continued until 25 April. The Chief Cabinet Secretary held regular press conferences twice a day and also on an ad hoc basis to provide information to the public on the accident and the views of the Government. More than 150 press releases were issued and 182 press conferences were held by NISA between 11 March and 31 May 2011 [3]. The results of environmental monitoring were presented at press conferences and press briefings by MEXT.

The Nuclear Safety Commission (NSC) held daily press conferences from 25 March to 24 April 2011, and eight press conferences were held by the NSC from 25 April to 19 May 2011 [3].

Joint press conferences between various organizations involved in the response were held from 25 April 2011 onward. This contributed to the consistency of the information that was provided [6]. The Local NERHQ published newsletters and distributed them to evacuation sites from April 2011 onward. Relevant information was also broadcast periodically via local radio stations [3].

Hotlines were established to answer inquiries from the public. For example, on 11 March 2011, NISA established a hotline to respond to queries relating to the evolution of the emergency and radiation safety, receiving approximately 15 000 calls between 17 March and 31 May 2011 [3]; on 13 March, a hotline of the NIRS was opened, with about 6500 calls answered by 11 April [116]; on 17 March 2011, MEXT and the JAEA opened a hotline, receiving a total of 17 500 calls by 18 May 2011 [3]. Fukushima Prefecture set up counselling services to address questions from residents about various aspects of radiation. Feedback from the public received via hotlines and counselling services identified the need for easily understandable information and supporting material [3].

From 12 March 2011 onward, the national Government posted information in English, Chinese and Korean on the web sites of the relevant ministries and agencies [117]. Information was provided to the diplomatic corps in Tokyo through regular briefings, held by the national Government on a daily basis from 13 March to 18 May 2011, and three times a week from 19 May onward [6]. A notification channel via fax and email to the diplomatic corps was also established. The diplomatic missions of Japan provided information to their host States, which was posted on web sites in a total of 29 different languages [3].

Beginning on 13 March 2011, joint press conferences were held, mostly on a daily basis, for the foreign news media by relevant national ministries and government agencies [6].

Challenges encountered in providing information to the international community related principally to the demands on human resources for translating materials and responding to information requests by telephone [117].

International Nuclear and Radiological Event Scale (INES) ratings were reported by Japan following the Fukushima Daiichi accident. The INES rating was used separately for the different units at the same site. The rating was revised to a higher level several times within one month. Revisions of the INES rating to a higher level were a cause of significant concern to the public and the news media.

3.3.4. International trade

Many activities and measures were initiated that were aimed at: (1) reassuring the public, industries and States of the safety of Japanese products; (2) facilitating international trade in Japanese products and preventing delays in distribution; and (3) providing advice and guidance to businesses and industries, in particular in Fukushima Prefecture [98, 99, 118, 119].

Most importing States introduced control measures on Japanese goods; many increased existing import controls or requested a certificate from the Government of Japan; and some banned the import of Japanese goods or those from certain regions of Japan (mostly agricultural products) for a period of time. In June 2011, Japan established a certification system for food products intended for export, which helped to reassure the public and other interested parties that controls were in place. This system was extended in September 2011 to cover shipping containers and some industrial products intended for export [120].

3.3.5. Waste management in the emergency phase

Arrangements for the management of radioactive waste established in Japan prior to the accident covered waste generated in facilities such as NPPs, but it did not include radioactive waste that had been generated in public areas [121]. Detailed strategies, guidelines and instructions for radioactive waste management were developed after the accident.

The ‘Near-Term Policy to Ensure the Safety for Treating and Disposing Contaminated Waste around the Site of the Fukushima Dai-ichi Nuclear Power Plants’ was issued by the NSC on 3 June 2011 [122]. This document provided dosimetric criteria for: recycled materials; protection of workers treating the materials; protection of members of the public in the vicinity of treatment facilities; and protection of members of the public in the vicinity of a disposal site. The NSC proposed that materials affected by the accident — i.e. debris, sludge from the water and sewage treatments, incinerated ash, trees, plants and soil resulting from decontamination activities — would be disposed of under proper management and that some materials may be considered for reuse. Products manufactured from these reused materials would be checked for contamination and managed appropriately before being released onto the market. Appropriate protective measures would ensure that radiation exposures on the part of workers and the public were kept as low as reasonably achievable [122].

The ‘Basic Policy for Emergency Response on Decontamination Work’ [123] was established by the NERHQ on 26 August 2011 as an interim policy until the ‘Act on Special Measures concerning the Handling of Environment Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with Tohoku District — Off the Pacific Ocean Earthquake that Occurred on March 11, 2011’ was fully in force. The Act was enacted on 26 August 2011, promulgated on 30 August 2011 — with portions of the Act entering into force the same day — and entered fully into force in January 2012 [124]. It outlined the management of the contaminated areas and included the assignment of responsibilities to the national and local governments, the operator and the public. It facilitated the transition from an emergency exposure situation to an existing exposure situation. It also formalized the long term management of environmental monitoring, decontamination measures and the designation, treatment, storage and disposal of soil and waste contaminated by radioactive material.

3.4. TRANSITION FROM THE EMERGENCY PHASE TO THE RECOVERY PHASE AND ANALYSES OF THE RESPONSE

Specific policies, guidelines, criteria and arrangements for the transition from the emergency phase to the recovery phase were not developed until after the Fukushima Daiichi accident. In developing these arrangements, the Japanese authorities applied the latest recommendations of the International Commission on Radiological Protection (ICRP).

Analyses of the accident and of the emergency response were performed and presented in the form of reports, including those issued by the Government of Japan, the operating organization (TEPCO), and two investigation committees created by the Government and the Parliament, respectively.[83]

After the accident, national emergency preparedness and response arrangements in Japan were, in many cases, revised to take account of the findings of these analyses and of relevant IAEA safety standards in the area of emergency preparedness and response.

3.4.1. Transition from the emergency phase to the recovery phase

In developing arrangements for the transition from the emergency phase to the recovery phase after the accident, the Japanese authorities decided to apply the latest recommendations of the ICRP [127–129]. The specific policies, guidelines and criteria, as well as overall arrangements for the transition from the emergency phase to the recovery phase, were developed after the accident [130]. This process included adjusting the protective actions and arrangements made early in the emergency response and taking account of the information available on the conditions in the affected areas (obtained primarily through comprehensive monitoring) [131, 132]. It also included consideration of the necessary longer term recovery operations.

These actions and arrangements primarily addressed the immediate needs arising during the transition process. The provisions for the protection of workers were gradually modified, depending on the work being undertaken [6, 96].

[83] Reports from academia and from the private sector were also issued (e.g. from the Atomic Energy Society of Japan and the Rebuild Japan Initiative Foundation) [125, 126].

On 17 April 2011, TEPCO issued a ‘roadmap’, outlining the steps towards recovery on the site (basic policy, targets and immediate actions in the areas of cooling, mitigation of consequences, and monitoring and decontamination) [24].

On 17 May 2011, METI issued a ‘Roadmap for Immediate Actions for the Assistance of Nuclear Sufferers’ [130]. This listed nine groups of actions divided into steps scheduled to be implemented over different periods connected to TEPCO’s roadmap. Step 1 had a target of mid-July, step 2 a target of around three to six months after achieving step 1, and step 3 for the mid-term period. This roadmap was intended to facilitate communication and preparations for the transition to long term recovery operations and the resumption of normal social and economic activity. It allocated responsibilities and specified other organizational aspects of the transition process and the objectives and conditions for termination of the emergency phase.

3.4.2. Analyses of the response

Analyses of the accident and the emergency response were undertaken by various bodies in order to identify lessons and to enhance, among other areas, emergency preparedness and response arrangements in Japan. A number of improvements in these arrangements were identified as a result.

For example, the report of the Government of Japan to the IAEA Ministerial Conference in June 2011 [3] presented lessons in the following areas important for emergency preparedness and response: (1) combined natural disaster and nuclear emergency; (2) environmental monitoring; (3) allocation of roles between central and local organizations; (4) communication in an emergency; (5) response to assistance from other States and communication with the international community; (6) modelling of the release of radioactive materials; and (7) criteria for evacuation and radiation protection guidelines in nuclear emergencies.[84]

The Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company, created by the Government, found that there was a need for Japan to take into account lessons from the international community and to include international standards, such as those developed by the IAEA, in its national guidelines [5].

TEPCO’s Fukushima Nuclear Accident Analysis Report [8] highlighted issues that were identified during the response to the emergency that included: emergency response organization; communication of information; transportation of materials and equipment; and radiation protection.

The report of the Fukushima Nuclear Accident Independent Investigation Commission established by the National Diet of Japan contained a recommendation for, among other things, reform of the national emergency preparedness and response system, including clarification of the roles and responsibilities of the Government, local government and operators in an emergency [7].

On the basis of these analyses and lessons identified, corrective actions were taken to strengthen emergency preparedness and response arrangements [133, 134]. A Nuclear Emergency Preparedness Commission was established within the Cabinet to ensure that nuclear emergency response policies would be implemented and promoted by the Government [134]. The NRA developed Nuclear

[84] An additional report was submitted to the IAEA in September 2011 [4]. It provided information on further developments and progress in addressing the lessons that had been identified in the first report issued in June 2011.

Emergency Response Guidelines[85] [136], also taking into account the IAEA safety standards in the area of emergency preparedness and response.

3.5. RESPONSE WITHIN THE INTERNATIONAL FRAMEWORK FOR EMERGENCY PREPAREDNESS AND RESPONSE

An extensive international framework for emergency preparedness and response was in place at the time of the accident, comprising international legal instruments, IAEA safety standards and operational arrangements.[86]

At the time of the accident, the IAEA had four roles in the response to a nuclear or radiological emergency: (1) notification and exchange of official information through officially designated contact points; (2) provision of timely, clear and understandable information; (3) provision and facilitation of international assistance on request; and (4) coordination of the interagency response.

The international response to the accident involved many States and a number of international organizations.

The IAEA liaised with the official contact point in Japan, shared information on the emergency as it developed, and kept States, relevant international organizations and the public informed. Communication with the official contact point in Japan in the early phase of the emergency response was difficult. The IAEA Director General's visit to Japan, and the subsequent deployment of liaison officers to Tokyo, improved communication between the IAEA and the contact point. The IAEA also sent expert missions to Japan and coordinated the inter-agency response.

Different States[87] either took or recommended different protective actions for their nationals in Japan in response to the accident. These differences were generally not well explained to the public and occasionally caused confusion and concern.

Relevant organizations participating in the Inter-Agency Committee on Radiological and Nuclear Emergencies regularly exchanged information. Joint press releases were also issued.

The IAEA, through its emergency arrangements, liaised directly with NISA, which was the official contact point in Japan [143]. Japan provided information in accordance with Article 3 of the Early Notification Convention.

The IAEA Secretariat shared information on the emergency as it developed and kept States, relevant international organizations and the public informed [143].

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[85] The Nuclear Emergency Response Guidelines were based on the interim report on the revision of the Regulatory Guide for Emergency Preparedness of Nuclear Facilities [93], which was issued in 2012 [135].

[86] The primary international legal instruments are the Convention on Early Notification of a Nuclear Accident and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency. The international safety standards in the area of emergency preparedness and response at the time of the accident were IAEA Safety Standards Series No. GS-R-2 [69] and No. GS-G-2.1 [68]. Safety Series No. 115 [137] also included elements related to emergency preparedness and response. The international operational arrangements comprised the Emergency Notification and Assistance Technical Operations Manual (ENATOM), IAEA Response and Assistance Network (RANET) and Joint Radiation Emergency Management Plan of the International Organizations (JPLAN).

[87] The primary responsibility for emergency preparedness and response for a nuclear or radiological emergency rests with the State, as does the primary responsibility for the protection of human life, health, property and the environment.

The IAEA's role at the time did not include providing a prognosis of the potential evolution of an accident or an assessment of the possible consequences. Its role in responding to an emergency at an NPP was expanded through the adoption of the IAEA Action Plan on Nuclear Safety [144]. This requested the Agency to provide Member States, international organizations and the general public with timely, clear, factually correct, objective and easily understandable information during a nuclear emergency on its potential consequences, including analysis of the available information, and prognoses of possible scenarios based on evidence, scientific knowledge and the capabilities of Member States.

Box 3.4. International framework for emergency preparedness and response for a nuclear or radiological emergency at the time of the accident

The primary responsibility for emergency preparedness and response for a nuclear or radiological emergency rests with the State, as does the primary responsibility for the protection of human life, health, property and the environment. The State is responsible for ensuring that emergency preparedness and response arrangements are in place at the national, regional, local and operating organization/facility levels. Where appropriate, the State is also responsible for ensuring the coordination of national arrangements for emergency preparedness and response with the relevant international arrangements to which the State has acceded or is otherwise a party (e.g. through bilateral and/or multinational agreements).

The international framework at the time of the accident comprised international legal instruments, IAEA safety standards and operational arrangements.

The Convention on Early Notification of a Nuclear Accident and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency, hereinafter referred to as the Early Notification Convention and the Assistance Convention, assign specific response functions and responsibilities to the IAEA and to the Parties. Various international organizations — by virtue of their statutory functions or of related legal instruments — have functions and responsibilities that encompass aspects of emergency preparedness and response [138, 139].

The IAEA safety standards in the area of emergency preparedness and response at the time of the accident were IAEA Safety Standards Series No. GS-R-2 (co-sponsored by seven international organizations) and IAEA Safety Standards Series No. GS-G-2.1 (co-sponsored by six international organizations) [68, 69]. The International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (IAEA Safety Series No. 115) also included parts that were related to emergency preparedness and response [137].

International operational arrangements comprised the Emergency Notification and Assistance Technical Operations Manual (ENATOM), the IAEA Response and Assistance Network (RANET) and the Joint Radiation Emergency Management Plan of the International Organizations (JPLAN) [140–142].

ENATOM facilitated the implementation of those articles of the Early Notification Convention and the Assistance Convention that were operational in nature, such as the provisions for notification and information exchange and the communication protocols for Contact Points identified under the Early Notification Convention and the Assistance Convention (through messages via faxes, telephone lines, emails and a secure and protected web site that could be responded to around the clock). These measures were the subject of regular exercises of various levels of complexity called convention exercises (ConvEx).

RANET was established to facilitate the provision of international assistance upon request and in compliance with the Assistance Convention. This system forms an operational mechanism to provide assistance in different technical areas, with the help of national capabilities registered in the network.

JPLAN describes a common understanding of how each organization acts during a response and in making preparedness arrangements for a nuclear or radiological emergency. It provides a mechanism for coordination, and clarifies the roles and capabilities of the participating international organizations. It is maintained by the Inter-Agency Committee on Radiological and Nuclear Emergencies (IACRNE), for which the IAEA provides the Secretariat. At the time of the accident, IACRNE comprised 15 international intergovernmental organizations.

Communication with the official contact point in Japan in the early phase of the emergency response was difficult. The visit to Japan from 17 to 19 March 2011 by the IAEA Director General, and the subsequent deployment of liaison officers to Tokyo, improved communication between the IAEA and the contact point [143].

Some States issued advice or a specific instruction for the protection of their nationals in Japan. Some advised their nationals in Japan to follow the orders and recommendations issued by the Japanese authorities in response to the emergency, while some States issued advice that differed from that provided by the Japanese authorities and other States [145]. Differences in the recommendations among States were due to various factors, including a lack of information on the evolving situation. These differences were generally not well explained to the public and occasionally caused confusion and concern.

The IAEA sent expert missions to Japan and coordinated the provision of Member State offers of assistance to Japan. The Assistance Convention was not invoked and RANET[88] was not utilized. States provided assistance to Japan directly. This support helped the Government of Japan to manage the nuclear emergency, which, together with the effects of the earthquake and tsunami, challenged the national response capability. One of the difficulties in accepting international assistance in the early stages of the national response was the absence of national arrangements for receiving such assistance [5, 143].

In accordance with its responsibilities, the IAEA Secretariat promptly activated the JPLAN and initiated coordination of the inter-agency response. Members of IACRNE exchanged information, focusing in particular on reaching a common understanding of the aftermath of the accident and coordinating efforts to keep the public informed. Regular video teleconferences were held until July 2011. Joint press releases were also issued.

As part of the bilateral agreements between the secretariats, the Food and Agriculture Organization of the United Nations (FAO), World Health Organization (WHO) and World Meteorological Organization (WMO) sent liaison officers to the IAEA to ensure effective coordination of the international response.

3.6. OBSERVATIONS AND LESSONS

A number of observations and lessons have been compiled as a result of the assessment of emergency preparedness and the response to the accident. The response to the accident highlighted lessons from past emergencies and confirmed the importance of being adequately prepared for an emergency response.

— **In preparing for the response to a possible nuclear emergency, it is necessary to consider emergencies that could involve severe damage to nuclear fuel in the reactor core or to spent fuel on the site, including those involving several units at a multi-unit plant possibly occurring at the same time as a natural disaster.**
  Consideration needs to be given to the possibility of a severe nuclear accident, irrespective of the cause, possibly involving more than one unit at a site and occurring simultaneously with a natural disaster, which could result in disruption at the site and of the local infrastructure. Systems,

[88] The IAEA Secretariat, together with Member States registered in RANET, continues to enhance this network on the basis of experience from the Fukushima Daiichi accident.

communications and monitoring equipment for providing essential information for both on-site and off-site responses need to be able to function under such circumstances.

Facilities where the response will be managed (e.g. on-site and off-site emergency response centres) need to be selected or designed to be operational under a full range of emergency conditions (radiological, working and environmental conditions), and need to be suitably located and/or protected so as to ensure their operability and habitability under such conditions.

— **The emergency management system for response to a nuclear emergency needs to include clearly defined roles and responsibilities for the operating organization and for local and national authorities. The system, including the interactions between the operating organization and the authorities, needs to be regularly tested in exercises.**

Arrangements are needed that integrate the response to a nuclear emergency with the response to natural disasters and human-made disasters (e.g. earthquakes, floods and fires).

The on-site response needs to be managed by personnel located at the site who have knowledge of the plant and of the situation. The on-site and off-site responses need to be coordinated based on pre-planned arrangements.

— **Emergency workers need to be designated, assigned clearly specified duties, regardless of which organization they work for, be given adequate training, and be properly protected during an emergency. Arrangements need to be in place to integrate into the response those emergency workers who had not been designated prior to the emergency, and helpers who volunteer to assist in the emergency response.**

The practical arrangements for the protection of emergency workers need to be addressed in a consistent manner and in adequate detail in relevant plans and procedures. Account needs to be taken of those who may not have been designated as emergency workers at the preparedness stage. Dose criteria for emergency workers need to be set in advance and applied in a consistent manner for the assigned emergency duties. Arrangements for ensuring the well-being of emergency workers (including contact with their families) need to be in place.

In addition, arrangements need to be pre-planned for members of the public (referred to as ‘helpers’) who volunteer to assist in response actions to be integrated into the emergency response organization and to be afforded an adequate level of radiation protection.

— **Arrangements need to be in place to allow decisions to be made on the implementation of predetermined urgent protective actions for the public, based on predefined plant conditions.**

These arrangements are necessary because decision support systems, including those using computer models, may not be able to predict the size and timing of a radioactive release (the ‘source term’), the movements of plumes, deposition levels or resulting doses sufficiently quickly or accurately in an emergency to be able to provide the sole basis for deciding on initial urgent protective actions.

At the preparedness stage, there is a need to develop an emergency classification system based on observable conditions and measurable criteria (emergency action levels). This system enables the declaration of an emergency shortly after the detection of conditions at a plant that indicate actual or projected damage to the fuel and initiation of predetermined, urgent protective actions for the public (in the predefined zones) promptly following classification of the emergency by the operator. This emergency classification system needs to cover a full range of abnormal plant conditions.

— **Arrangements need to be in place to enable urgent protective actions to be extended or modified in response to developing plant conditions or monitoring results. Arrangements are also needed to enable early protective actions to be initiated on the basis of monitoring results.**

At the preparedness stage, there is a need to establish arrangements to, among other things: (1) define emergency planning zones and areas; (2) establish dose and operational criteria (levels of measurable quantities) for taking urgent protective actions and other response actions, including dealing with special population groups within emergency zones (e.g. patients in hospitals); (3) enable urgent protective actions to be taken before or shortly after a release of radioactive material; (4) enable prompt establishment of access controls in areas where urgent protective actions are in place; (5) extend protective actions beyond the established emergency planning zones and areas if necessary; (6) establish dose and operational criteria for taking early protective actions and other response actions (e.g. relocation and food restrictions) that are justified and optimized, taking into account a range of factors such as radiological and non-radiological consequences, including economic, social and psychological consequences; and (7) establish arrangements for revision of operational criteria for taking early protective actions on the basis of the prevailing conditions.

— **Arrangements need to be in place to ensure that protective actions and other response actions in a nuclear emergency do more good than harm. A comprehensive approach to decision making needs to be in place to ensure that this balance is achieved.**

  These arrangements need to be developed with a clear understanding of the full range of possible health hazards presented in a nuclear emergency and of the potential radiological and non-radiological consequences of any protective actions.

  Protective actions need to be taken in a timely and safe manner, taking into account possible unfavourable conditions (e.g. severe weather or damage to infrastructure). Preparations in advance are necessary to ensure the safe evacuation of special facilities, such as hospitals and nursing homes; continuing care or supervision must be provided for those who need it.

— **Arrangements need to be in place to assist decision makers, the public and others (e.g. medical staff) to gain an understanding of radiological health hazards in a nuclear emergency in order to make informed decisions on protective actions. Arrangements also need to be in place to address public concerns locally, nationally and internationally.**

  Public concerns need to be effectively addressed in a nuclear emergency. This includes the means to relate measurable quantities (e.g. dose rates) and projected radiation doses to radiological health hazards in a manner that allows decision makers (and the public) to make informed decisions concerning protective actions. Addressing public concerns contributes to mitigating both the radiological and the non-radiological consequences of the emergency.

  International concerns could be addressed, in part, by means of certification systems to demonstrate that tradable goods meet international standards and to reassure importing States and the public.

— **Arrangements need to be developed at the preparedness stage for termination of protective actions and other response actions, and for transition to the recovery phase.**

  At the preparedness stage, there is a need to plan for the transition from the emergency phase to the long term recovery phase and for resumption of normal social and economic activities. The arrangements need to: (1) establish formal processes to decide on the termination of protective actions and other response actions; (2) clearly allocate responsibilities; (3) establish criteria for the termination of protective actions and other response actions; and (4) provide a strategy and process for consulting the public.

— **Timely analysis of an emergency and the response to it, drawing lessons and identifying possible improvements, enhances emergency arrangements.**

  Such an analysis needs to include a review of all relevant arrangements, including national laws and regulations, allocation of authorities and responsibilities, emergency response plans and procedures, facilities, equipment, training and exercises. Analysis provides a basis for revision of the arrangements, as necessary. The adequacy of revised emergency arrangements needs to be demonstrated through exercises.

— **The implementation of international arrangements for notification and assistance needs to be strengthened.**

  Awareness of international arrangements for notification and assistance in a nuclear or radiological emergency, as well as existing operational mechanisms, needs to be increased, including mechanisms and procedures for notification and information exchange, for requesting and providing international assistance, etc. There is a need for enhanced training and exercises on the operational aspects of the Early Notification Convention and the Assistance Convention.

Participation in existing mechanisms for the provision of international assistance under the Assistance Convention needs to be an integral part of national emergency preparedness efforts. Arrangements need to be in place at the preparedness stage for requesting and receiving assistance (on the basis of bilateral agreements or under the Assistance Convention) in a nuclear or radiological emergency.

Lists of officially designated contact points, as required under the Early Notification Convention and the Assistance Convention, need to be continuously updated and prepared for immediate requests for information from the IAEA.

Application of the IAEA safety standards on emergency preparedness and response at the national level would improve preparedness and response, facilitate communication in an emergency and contribute to the harmonization of national criteria for protective actions and other response actions.

— **There is a need to improve consultation and sharing of information among States on protective actions and other response actions.**

Consultation and sharing of information on protective actions and other response actions among States in an emergency helps to ensure that actions are taken consistently. In addition, a clear and understandable explanation of the technical basis for decisions on protective actions and other response action is crucial in order to increase public understanding and acceptance at both the national and international levels.

4. RADIOLOGICAL CONSEQUENCES

Section 4 considers the radiological consequences of the accident at the Fukushima Daiichi NPP for people and the environment. The radiological consequences of the accident have been addressed by a number of international organizations and bodies. WHO issued a preliminary estimation of radiation doses [146] and subsequently assessed the risk attributed to the accident [147]. More recently, UNSCEAR estimated radiation levels and effects [148]. Radiation protection lessons have been compiled by the ICRP [149, 150]. Other international organizations, notably FAO and WMO, have also provided relevant information. Some of these international activities are described in Box 4.1.

Box 4.1. International activities related to the radiological consequences of the accident at the Fukushima Daiichi NPP

In addition to the IAEA, other international bodies have been active in addressing the radiological consequences of the accident at the Fukushima Daiichi NPP:

— The World Health Organization (WHO), a specialized agency of the United Nations concerned with public health, issued a preliminary estimate of the radiation doses incurred due to the accident [146] and, subsequently, a health risk assessment [147].
— The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), which reports to the United Nations General Assembly, reported its estimates of the levels and effects of radiation exposure attributable to the accident, including a considerable amount of data on environmental radioactivity and radiation doses [148].
— The International Commission on Radiological Protection (ICRP), a non-governmental international body of experts that issues widely used recommendations on radiological protection, issued a review of radiological protection issues during and after the accident, aimed at improving the international system of radiological protection [149, 150].
— The Food and Agriculture Organization of the United Nations (FAO), a specialized agency of the United Nations involved in agriculture, forestry and fisheries practices for ensuring good nutrition and food security for all, worked in partnership with the IAEA, through the Inter-Agency Committee on Radiological and Nuclear Emergencies (IACRNE), in preparing for and responding to nuclear or radiological emergencies affecting food, agriculture, forestry and fisheries, and compiled a significant database on radionuclide concentrations in food due to the accident [151].
— The World Meteorological Organization (WMO), a specialized agency of the United Nations for meteorology, operational hydrology and related geophysical sciences, issued an evaluation of meteorological analyses for the radionuclide dispersion and deposition from the accident [152].
— The Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD/NEA) reported on the nuclear safety response and lessons learned from the accident [153].
— These and other organizations such as the United Nations Environment Programme (UNEP), the International Labour Organization (ILO), the Pan American Health Organization (PAHO), and the European Commission (EC) co-sponsor international safety standards that are issued under the aegis of the IAEA. WHO establishes Guidelines for Drinking-water Quality to be used in existing exposure situations, which contains parameters for radioactivity in drinking water [154]. The FAO and WHO Codex Alimentarius Commission establishes the Codex Alimentarius, a collection of internationally harmonized food standards to protect the health of consumers and to ensure fair practices in the international food trade, which contain standards on the presence of radionuclides in food [155].

Official bodies in many States, including Japan, carried out numerous evaluations of the radiological consequences of the accident at the Fukushima Daiichi NPP (e.g. Ref. [5]). National professional radiation protection organizations, both in Japan and elsewhere, identified important lessons for radiation protection (e.g. Ref. [156]). Fukushima Prefecture launched the Fukushima Health Management Survey [157] in June 2011 [158]. This survey, which is described in Box 4.2, was discussed at the International Expert Symposium in Fukushima [159, 160].

Box 4.2. The Fukushima Health Management Survey

The Fukushima Health Management Survey is a general examination and investigation of the health situation of people in Fukushima Prefecture [157]. It is based on a series of questionnaires and has the following objectives: "(1) to assess residents' radiation dose, and (2) to monitor residents' health conditions, which result in disease prevention, early detection and early medical treatment, thereby (3) to maintain and promote their future health" [161].

Following the response, effective doses due to external exposures incurred in the four months following the nuclear accident were estimated by the National Institute of Radiological Sciences (NIRS) on the basis of recorded movements of respondents, in combination with an understanding of the relevant radiation levels. In addition, there were detailed surveys that included: (1) thyroid ultrasound examinations, covering roughly 370 000 residents aged 0 to 18 years at the time of the nuclear accident (the initial screening was performed within the first three years after the accident, followed by complete thyroid examinations from 2014 onwards, and regular monitoring of the residents thereafter); (2) a comprehensive health check aimed at the early detection and treatment of diseases, as well as the prevention of lifestyle related diseases, having as a main target 210 000 former residents of evacuation zones whose lifestyle changed drastically after the accident (additional tests such as differential leukocyte counts, are being performed apart from the routine tests included in general medical check-ups at the workplace or by the local government); (3) a Mental Health and Lifestyle Survey aimed at providing adequate care, mainly for evacuees who are at a higher risk of developing mental health problems such as post-traumatic stress disorder, anxiety and stress; and (4) a pregnancy and birth survey aimed at providing appropriate medical care and support to mothers who were given a Maternal and Child Health Handbook between 1 August 2010 and 31 July 2011, as well as to their children. (This survey is being updated every year to take account of new data, particularly on pregnancy and births [162].)

The Fukushima Medical University received a mandate to conduct the health survey from Fukushima Prefecture and launched the Radiation Medical Science Center for the Fukushima Health Management Survey to conduct the basic survey of external dose estimates and four detailed surveys. The survey and its results are assessed periodically by the Prefectural Oversight Committee Meeting for the Fukushima Health Management Survey.

This section builds on these international and national data, evaluations and estimates by making use of new information, in particular information provided by the Japanese authorities to the IAEA for this report. It should be noted that the estimates in various international and national reports have been performed at different times and with different levels of information. Thus, while some direct comparisons can be made between the various results, differences between the data, methodology and dates of the studies make any detailed comparison difficult.

Quantities and units

Specialized international quantities[89] and units[90] [163, 164] were used for monitoring and reporting radiological data of the accident. The fundamental international radiation protection quantities and units which are used in this report are briefly described in Box 4.3.

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[89] The term 'quantity' is used in this report in its scientific sense of being a measurable property, in this case of phenomena such as radioactivity or radiation.

[90] The unit of a quantity is a definite amount of such a quantity, which is used as a standard for measurement.

Box 4.3. The fundamental radiation protection quantities and units used in this report

The quantity used to describe radioactivity is termed *activity* and its unit of measurement is called *becquerel* (Bq). One becquerel represents an extremely small level of activity. For example, the human body contains around 5000 Bq of naturally radioactive potassium-40 (for a person weighing 70 kg, with 140 g of potassium in the body). Therefore, in order to measure the large releases of radionuclides from the accident, a suitable prefix, such as peta (P) is used in this report: 1 petabecquerel (PBq) equals 10^{15} Bq.

The release of radioactive material led to the exposure of people to ionizing radiation, through both *external exposure*, when the activity was outside the body, and *internal exposure*, when the radionuclides were incorporated into the body (e.g. by ingestion or inhalation or through the skin). The quantity describing the mean radiation exposure incurred by organs and tissues is termed *absorbed dose* and its unit of measurement is joule per kilogram called *gray* (Gy), often expressed as thousandths of a Gy, or *milligrays* (mGy).

For radiation protection purposes, the absorbed dose has to be weighted because different types of radiation have varying levels of effectiveness in causing harm, and different organs and tissues have different sensitivities to radiation exposure. The quantity resulting from the application of *radiation weighting factors* to the absorbed dose in organs and tissues is called *equivalent dose*, and its unit is termed *sievert* (Sv), usually expressed as thousandths of a Sv, or *millisieverts* (mSv). In the report, thousandths of mSv, or *microsieverts* (μSv), are also used. The quantity resulting from the application of *tissue weighting factors* is called *effective dose* and is also measured in mSv. While there is some variation between individuals in the effect of a given exposure to radiation, for radiation protection purposes doses are estimated as though delivered to a defined ideal reference individual, as it is not feasible to take into account individual differences.

The *absorbed dose* and the *equivalent dose* are used for doses incurred by tissues and organs. Given the type of radiation involved, in all radiation exposures from the accident (except insignificant exposures to neutrons) the reported absorbed doses were numerically equal to the corresponding equivalent doses and vice versa. The *effective dose* is used for assessing the whole body implications. An internal exposure will continue as long as any of the inhaled or ingested radioactive substances remain in the body. The *committed dose* caused by this continuing exposure is calculated as that dose which is expected over the exposed person’s lifetime.

The following estimates of effective doses commonly incurred are provided as a reference [165]:

- Global natural background radiation delivers an annual average effective dose of 2.4 mSv, with a typical range of 1–13 mSv, and with sizeable population groups incurring up to 10–20 mSv, and in extreme cases up to around 100 mSv.
- The globally averaged annual effective dose due to medical radiodiagnosis is 0.6 mSv, and a single computed tomography examination can deliver an effective dose of around 10 mSv. (It should be noted that medical exposure is usually localized to part of the body, i.e. it is not uniformly distributed in the body.)

Other quantities used in practice are derived from the fundamental radiation protection quantities. Box 4.4 describes some of these derived quantities and a number of related issues. The many quantities and units were not easily understandable by the public in the aftermath of the accident. The ICRP, in its assessment of radiological protection issues arising during and after the accident, concluded that international action should be taken in the future to ensure that “any confusion on protection quantities and units be resolved” [149].

Box 4.4. Measurement quantities and operational terms

The protection quantities *equivalent dose* and *effective dose* are not directly measurable. Therefore, instruments for measuring external exposure, either incurred by persons or present in the environment (or in the ambience), are calibrated against operational quantities called *personal dose equivalent* and *ambient dose equivalent*, respectively. These are *proxies* of the protection quantities, i.e. a measured quantity used to infer the value of the quantity of interest, and they are also measured in mSv. These operational quantities were used for monitoring in the aftermath of the accident and are used in the report when referring to monitored values.

Depending on the type of exposure situation, particular terms are used to facilitate the explanation of the concept of exposure control, as follows:

- In *planned exposure situations*[1], the *additional dose* expected to be added by a planned operation is used. For these situations, the relevant individual dose restrictions are known as *dose limits*. Dose limits are values of the additional effective doses or the additional equivalent doses to individuals expected from a planned exposure situation that are not to be exceeded; they are applicable to the additional individual doses from external exposure in a given period of time plus the additional individual dose commitment from intakes of radionuclides in that time period.
- In *emergency exposure situations*[2], three concepts of dose are used: (1) the *projected dose* (the dose that would be expected to be received if no protective actions were taken); (2) the *avertable dose* (the dose that could be averted if a protective action was taken); and (3) the *residual dose* (the dose expected to be incurred in the *existing exposure situations*[3] remaining after protective actions have been terminated). *Reference levels* are applied to residual doses as guidance levels for optimizing protection. These represent the level of dose "above which it is judged to be inappropriate to plan to allow exposure to occur and below which optimization of protection should be implemented" [129].

There are also quantities derived from *activity*, such as quantities related to the presence of radioactivity in the environment expressing, for instance, the activity on land or in products of public consumption. Relevant derived quantities are the *deposition density*, which expresses the *activity per unit area,* usually expressed in Bq/m^2; the *specific activity*, which expresses the *activity per unit mass* or *weight,* usually expressed in Bq/kg; and the *activity concentration*, which expresses the *activity per unit volume,* usually expressed in Bq/L. These quantities are usually referred to as *contamination*. This term is formally defined in international standards as: (1) the *presence* of radionuclides on surfaces, or within solids, liquids or gases (including the human body), where their presence is unintended or undesirable; or (2) the *process* giving rise to their presence in such places, in both cases with no indication of the magnitude of the hazard involved. However, the term *contamination* carries a connotation of impurity or danger that is not intended in its formal denotation as presence or process.

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[1] *Planned exposure situations* arise from the planned operation of radiation sources (e.g. the normal operation of the Fukushima Daiichi NPP) or from planned operations that result in exposure from sources. Since provisions for protection and safety can be made in advance, exposures can be restricted from the outset. In planned exposure situations, a certain level of exposure is expected to occur.

[2] *Emergency exposure situations* include situations of exposure that arise as a result of an accident and require prompt action in order to avoid or reduce adverse consequences.

[3] *Existing exposure situations* are situations of exposure that already exist when a decision on the need for control needs to be taken and include exposure due to residual radioactive material arising from a nuclear or radiological emergency after an emergency exposure situation has been declared to be ended.

Uncertainties

The estimates of the radiological consequences of the accident are subject to a number of uncertainties, which are often expressed as the range of likely values of the relevant quantities. Some of these uncertainties have been accounted for after a statistical analysis of the variables involved, for example in the estimates of personal radiation dose due to external exposure, but not all uncertainties have been resolved. While the risks from radiation exposure are better understood than risks from exposure to other agents, it is important that relevant uncertainties are addressed and communicated properly [166, 167].

Statistical analyses

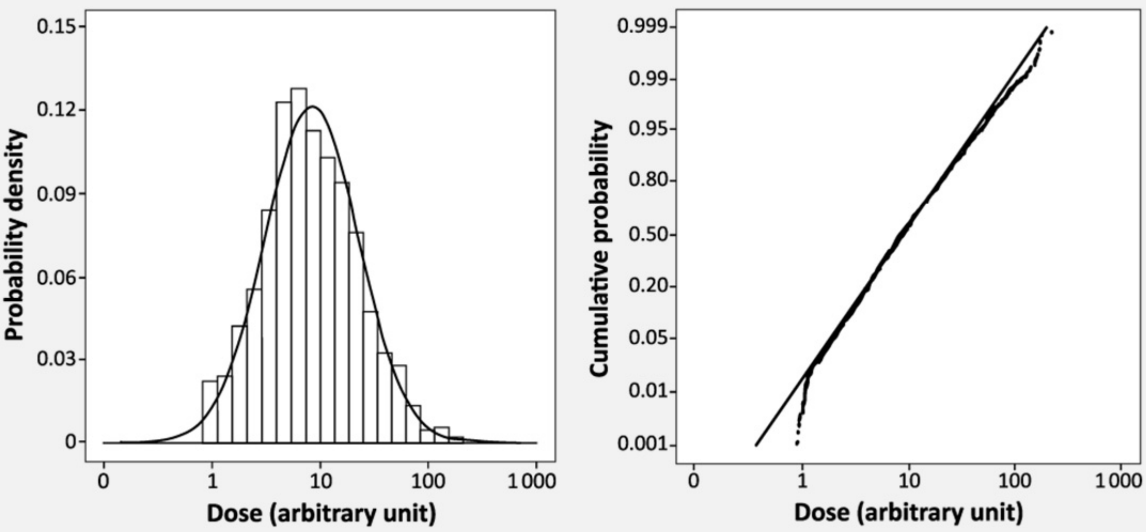
In order to deal with uncertainties, statistical analyses of some relevant variable data have been performed. The variables include specific activity in food and, in particular, personal radiation doses. The analyses of radiation doses covered estimates based on the use of questionnaires and ambient and environmental radiation data, and those based on personal monitoring through personal dosimeters and whole body counting of incorporated radioactivity. The basis for the statistical analyses is summarized in Box 4.5, which describes probability distributions of data, in particular the *log-normal probability distribution* that was specifically used in the analyses. There are many circumstances in which multiple measurement data, including measurements of environmental quantities, are expected to be statistically distributed following an approximate log-normal probability distribution. A large amount of information is available on the statistical distribution of doses incurred by exposed populations, which shows approximate log-normal distributions. Relevant evidence came from UNSCEAR occupational dose estimates [168] and also from the analysis of public doses from the accident at the Chernobyl NPP in 1986 [169]. However, a number of issues have been presented in the analyses of the data submitted following log-normal distributions, and some of them are summarized in Box 4.6.

Box 4.5. Statistical analysis of estimated and measured data

Some relevant data used in this report — notably data on personal doses and also on activity in food — were analysed statistically. The values of the variable quantity (e.g. the values of activity or dose) were classified according to their frequency distribution. For this, the whole range of data was *binned*, namely grouped together in *bins,* or a series of small interval ranges of numerical values, into which the data were sorted for analysis. The data in each bin were displayed adjacent one to another in a *histogram* that is a diagram consisting of rectangles representing the bins, whose positions represent the values of the quantity and whose dimension represents the number of data in every bin. The histogram was then normalized, multiplying the values of the rectangles by a factor that makes the total area of the rectangles equal to 1. When sufficient data are available and the intervals become very small, the histogram tends towards a smooth curve termed a *probability density function* that describes the relative likelihood for the quantity (e.g. the activity in food or the dose incurred by people) to have a given value.

While the most common distribution is the *normal* (or Gaussian) distribution, represented by a bell shaped probability density function that is symmetric with respect to the maximum probability, the most relevant distribution for the purpose of the report is the *logarithmic-normal* or *log-normal* distribution. The log-normal distribution is a probability distribution of a quantity, such as the activity or the dose, whose logarithm is normally distributed. Thus, the log-normal probability density function is symmetrical with respect to the maximum only when displayed as a function of the logarithm of the quantity (e.g. the logarithm of the activity or the logarithm of the dose) rather than as a function of the quantity. An example of such a log-normal probability distribution, showing an idealized histogram and its probability density function, is illustrated on the left hand side of the figure below.

Box 4.5. Statistical analysis of estimated and measured data (cont.)



The probability density function can be *integrated*, meaning that the values of the bins in the normalized histogram can be summed, from the lower to the higher values of the quantity. This summation, as a function of the quantity, is termed a *cumulative probability function* and describes the likelihood that a quantity with a given probability distribution will be found to have a value less than or equal to the value.

The *log-normal cumulative probability function* could be plotted as a straight line in a coordinate plane of abscissas representing the quantity (e.g. the dose) calibrated logarithmically versus ordinates representing the cumulative probability calibrated as a *normal* function. An example of such representation is shown on the right hand side of the figure above, where the integral of the actual experimental data of the bins in the left-hand figure is plotted vis-à-vis the straight line.

Box 4.6. Issues with log-normal distribution of the data

While the binning of data sets usually results in a relatively smooth distribution of the bin levels, for some data sets of the submitted information this was not the case. For these data sets the bin distributions look distorted, usually due to the accumulation of a large amount of data in a particular bin. For instance, in some data sets all the values near the detection limit were accumulated in one (initial) bin without discrimination, while higher values were properly discriminated. In the statistical analyses the decision was made to distribute this misleadingly accumulated data according to a probability density distribution derived from the actual data (using its relevant statistical values, such as mean and standard deviation) and, on this basis building up a conjectural, randomly created, distribution including a larger number of bins. The result is a conceptual histogram which is tailored to the statistical values of the real data and to which a smooth probability density curve can be fit. This probability density function, which describes how the distribution should ideally look like if the data have been sufficiently detailed and discriminated, is presented together with the cumulative probability function in the relevant figures of the report. In one of the figures the actual distribution of bins is also presented for comparison.

Box 4.6. Issues with log-normal distribution of the data (cont.)

While exact adherence to the log-normal distribution may not be observable across the full range of data, explanations of the deviations, in particular deviations from the straight line in the cumulative probability, can usually be elaborated and they form an important part of the analysis. A cause of deviation is uncertainty originating both in the measurements themselves and in the statistical nature of the sampling process. A particular problem in the analyses of incurred doses, which is typical of accidental situations, was the likely inhomogeneous nature of the cohorts of exposed people. Other causes included constrained distribution in the data; for instance, at high doses, there might be higher than expected cumulative probability (i.e. fewer people than expected are incurring high dose) with the most likely explanation that dose restrictions have been applied successfully. If they are higher than expected in the low dose range (i.e. more people than expected are incurring low doses), a plausible explanation is that a dose equal to the detection limit has been (misleadingly) assigned to all people with doses below these levels; conversely, if they are lower than expected it might mean that a zero dose has been assigned (again misleadingly) to everybody with doses below the detection level. Sometimes deviations from the straight line became ostensible due to the high level of inconsistency in the local data; for example, when two different population groups were mixed, such as evacuees with residents that remained in the area, there may be evidence of the change in the slope of the cumulative probability distribution, with each sector reflecting the doses received in each area. Sometimes there were protracted collections of information that distorted the data, e.g. due to radioactive decay over time. Deviations from linearity in a log-normal cumulative probability plot may be used to make plausible inferences about the underlying data.

4.1. RADIOACTIVITY IN THE ENVIRONMENT

The accident resulted in the release of radionuclides to the environment. Assessments of the releases have been performed by many organizations using different models. Most of the atmospheric releases were blown eastward by the prevailing winds, depositing onto and dispersing within the North Pacific Ocean. Uncertainties in estimations of the amount and composition of the radioactive substances were difficult to resolve for reasons that included the lack of monitored data on the deposition of the atmospheric releases on the ocean.

Changes in the wind direction meant that a relatively small part of the atmospheric releases were deposited on land, mostly in a north-westerly direction from the Fukushima Daiichi NPP. The presence and activity of radionuclides deposited in the terrestrial environment were monitored and characterized. The measured activity of radionuclides decreases over time due to physical decay, environmental transport processes and cleanup activities.

In addition to radionuclides entering the ocean from the atmospheric deposition, there were liquid releases and discharges from the Fukushima Daiichi NPP directly into the sea at the site. The precise movement of radionuclides in the ocean is difficult to assess by measurements alone, but a number of oceanic transport models have been used to estimate the oceanic dispersion.

Radionuclides such as ^{131}I, ^{134}Cs and ^{137}Cs were released and found in drinking water, food and some non-edible items. Restrictions to prevent the consumption of these products were established by the Japanese authorities in response to the accident.

4.1.1. Releases

Many assessments of the releases of radionuclides from the accident at the Fukushima Daiichi NPP have been performed using established mathematical models and methods and associated computer codes (see Refs [170–177]).

In the early phase of the accident, the noble gases ^{85}Kr and ^{133}Xe, with half-lives of 10.76 years and 5.25 days, respectively, contributed to external exposure from the plume of the atmospheric releases. The short lived ^{131}I, with a half-life of 8.02 days, contributed to the equivalent doses to the thyroid gland if ingested or inhaled. The longer lived ^{134}Cs and ^{137}Cs, with half-lives of 2.06 years and 30.17 years, respectively, contributed to both equivalent doses and effective doses through external and internal exposure. While ^{131}I decays relatively quickly, it can give rise to relatively high equivalent doses to the thyroid gland. In some areas, ^{137}Cs may continue to be present in the environment, and without remediation it could remain a contributor to effective doses to individuals.

Radionuclides of strontium, ruthenium and some actinides (e.g. plutonium) were also released in varying amounts. As indicated in Section 2.1, neutrons were detected near the main gate of the plant (which is around 1 km away from Units 1–3), between 05:30 and 10:50 on 13 March. It is estimated that the neutrons came from the spontaneous nuclear fission of radionuclides that could have been released as a result of damage to the reactor core. Such a phenomenon was predictable, and the presence of these radionuclides at relatively low levels has been reported.

Releases to the atmosphere

Noble gases were a significant part of the early releases from the Fukushima Daiichi NPP; around 6000–12 000 PBq of ^{133}Xe are estimated to have been released (or 500–15 000 PBq, if early estimates are included in the evaluation). The mean total activity of ^{131}I released was around 100–400 PBq, and that of ^{137}Cs was around 7–20 PBq (or 90–700 PBq and 7–50 PBq, if early estimates are included). The releases from the accident are estimated to be approximately one tenth of the releases from the accident in 1986 at the Chernobyl NPP [169, 178, 179]. Most of the releases were dispersed over the North Pacific Ocean; as a result, the amount and isotopic composition of material released (the 'source term') could not be reconfirmed by environmental measurements of the radionuclide deposits [177].

Releases into the sea

Most of the atmospheric releases dispersed over the North Pacific Ocean fell on the oceanic surface layer. There were direct releases and also discharges into the sea at the site, with the primary source of highly radioactive water from a trench at the Fukushima Daiichi NPP. The peak radioactive releases were observed at the beginning of April 2011. The direct releases and discharges of ^{131}I into the sea were estimated to be 10–20 PBq. The direct releases and discharges of ^{137}Cs were estimated by most analyses to be in the range of 1–6 PBq, but some assessments reported estimates of 2.3–26.9 PBq [175].

4.1.2. Dispersion

Many theoretical models have been used to estimate the dispersion patterns. Extensive measurements of activity concentration of ^{131}I, ^{134}Cs and ^{137}Cs in the environment, including in air, soil, sea water, sediments and biota, were performed and have also been used for estimating the dispersion of the releases.

Atmospheric dispersion

The transport of the atmospheric radioactive releases was directed mainly to the east and north of Japan, following the prevailing wind direction, and then around the globe. Figure 4.1 presents an example of the many atmospheric transport models that were used to estimate the atmospheric transport of the various radionuclides and their deposition patterns, which describe the results of modelling the global dispersion of ^{137}Cs [180]. The figure illustrates activity concentration in air by using the original code of colours of the reference, where small changes in the degree of the colour correspond to one order of magnitude change in the activity concentration. The illustration is intended to support the conclusion that activity concentration in the atmosphere decreased noticeably with distance from the Fukushima Daiichi NPP.

Highly sensitive radiation monitoring networks detected extremely low levels of radioactivity attributable to the accident as far away as Europe and North America. However, the effects of these releases on the level of global environmental background radioactivity were negligible.

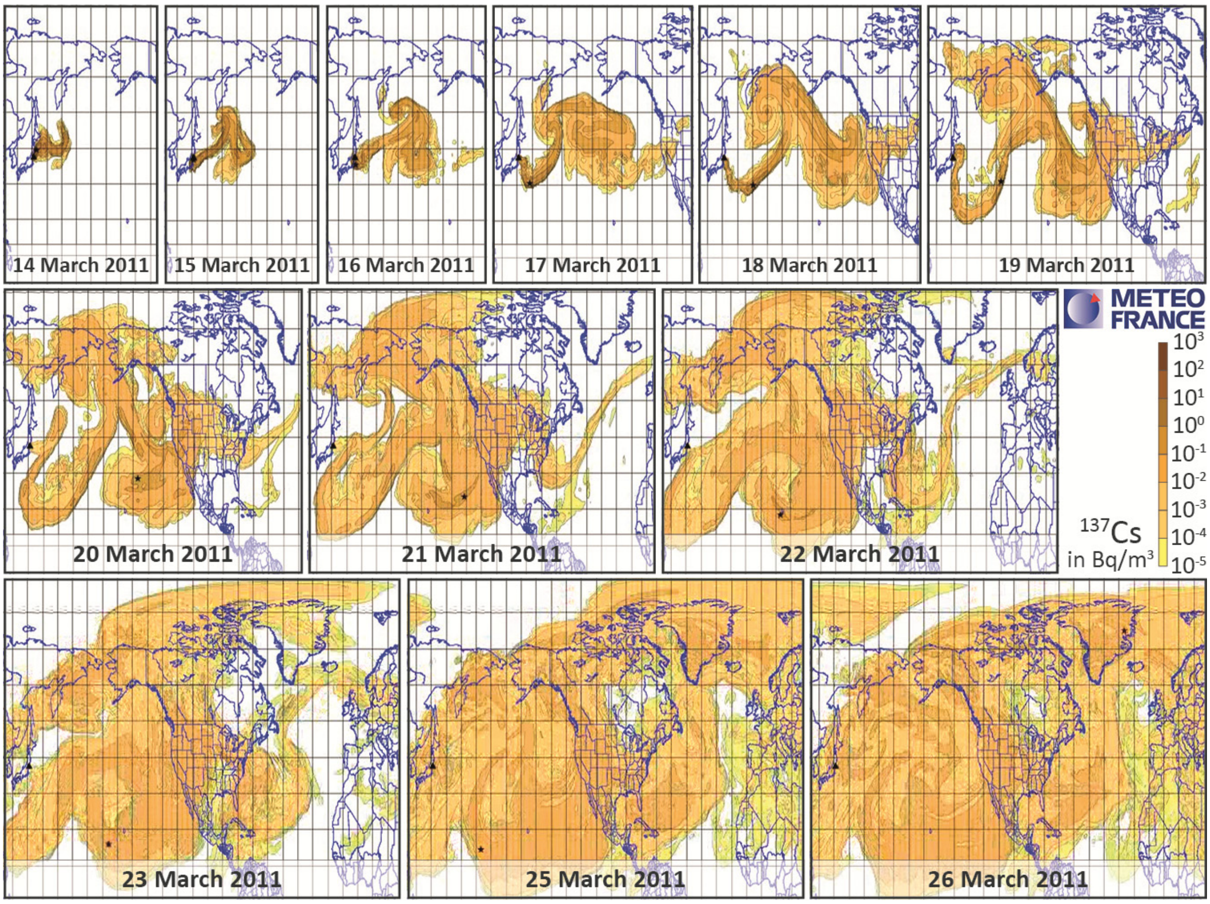


FIG. 4.1. Results from one of the global models of the atmospheric dispersion of ^{137}Cs, presented in its original code of colours (see Ref. [180] for details) (Illustration courtesy of Meteo-France).

Oceanic dispersion of direct releases and discharges into the sea at the site

Most of the released and discharged radionuclides that entered into the sea at the site moved eastward with the Kuroshio current[91], were transported over large distances via the North Pacific Ocean gyre[92] and became highly diluted in the sea water [181]. Radioactivity spread over large oceanic distances

[91] The Kuroshio current is a northward flowing ocean current on the western side of the North Pacific Ocean that flows past the Fukushima Daiichi NPP.

[92] The North Pacific Ocean gyre is one of the five major oceanic gyres, covering most of the North Pacific Ocean; it has a clockwise circular pattern and is formed by the North Pacific Ocean current to the north, the California current to the east, the north equatorial current to the south, and the Kuroshio current to the west.

and was detected in extremely small amounts far away from the accident, sometimes via pathways through oceanic biota, such as blue-fin tuna fish [182].

While the precise movement of radionuclides in the ocean is difficult to assess by measurements alone, a number of oceanic transport models were used to assess their dispersion patterns. Figure 4.2 illustrates examples of these models describing the dispersion of ^{137}Cs in the North Pacific Ocean. The figure uses the original code of colours employed in each particular reference. As in the case of atmospheric dispersion, small changes in the degree or tone of the colours correspond to one order of magnitude change in the activity concentration. The illustration is intended to support the conclusion that activity in the ocean decreased noticeably with distance from the Fukushima Daiichi NPP. All models show that the activity of ^{137}Cs in the ocean was very low.

(a)

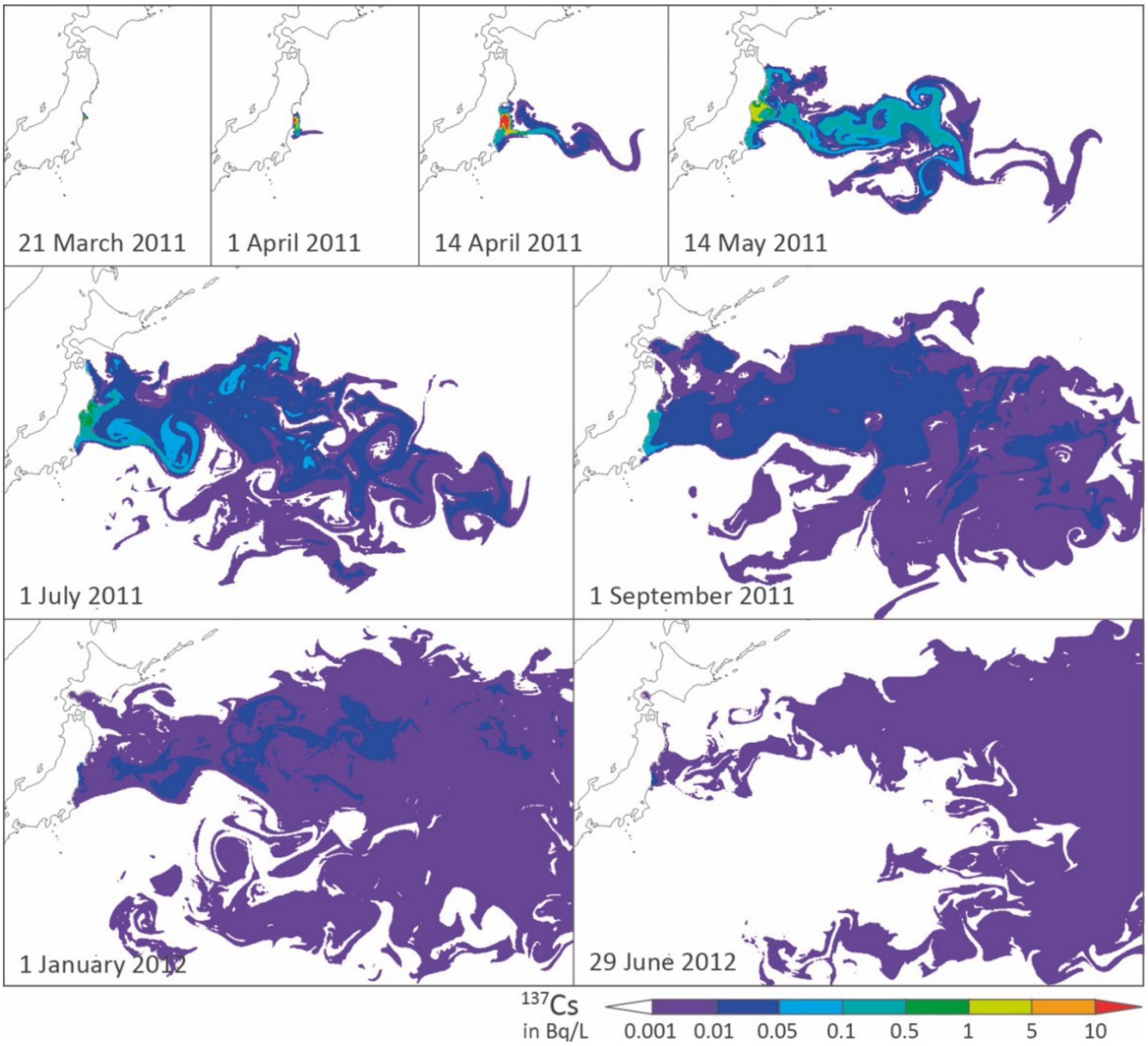
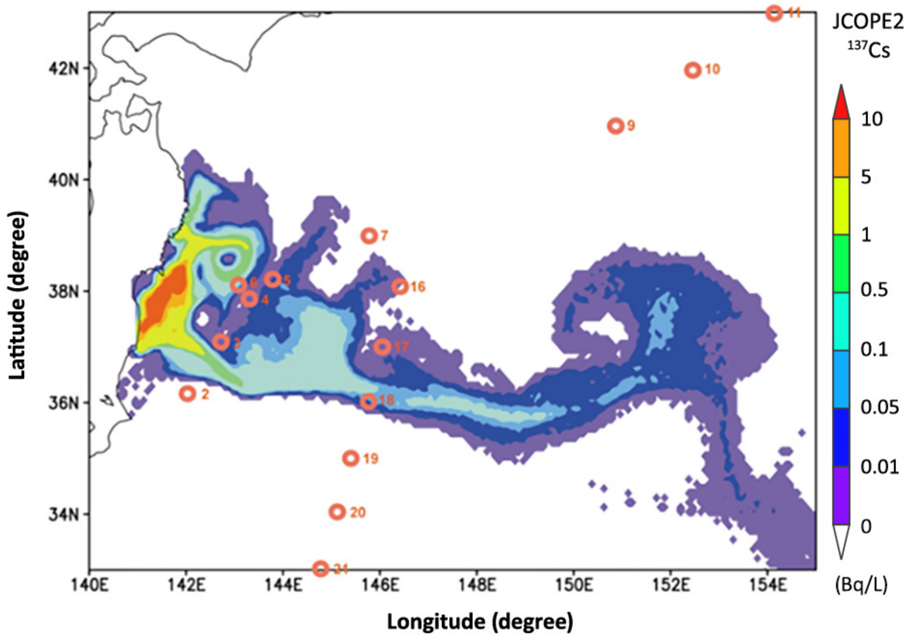


FIG. 4.2. Various oceanic models have been used to estimate the activity concentration of ^{137}Cs in sea water (the code of colours and the units used are those employed in the references): (a) an example of modelling contaminated waters from 21 March 2011 to 29 June 2012 [183, 184].

(b)



(c)

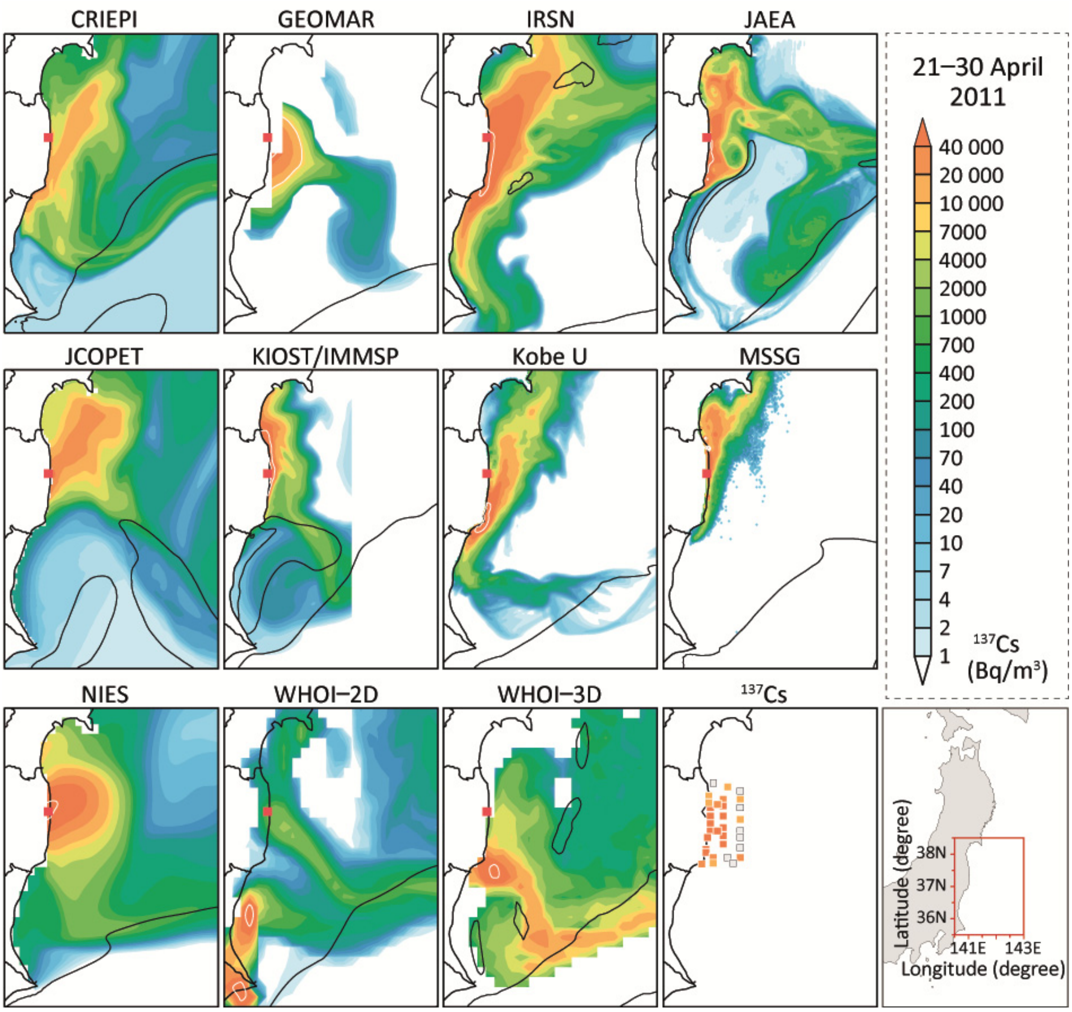


FIG. 4.2. (cont.) Various oceanic models have been used to estimate the activity concentration of ^{137}Cs in sea water (the code of colours and the units used are those employed in the references): (b) simulated horizontal distribution of ^{137}Cs in surface waters between 14 and 26 April 2011 [185]; (c) horizontal distribution of the ^{137}Cs concentrations averaged over a ten day period from 21 to 30 April 2011, with the name of the models indicated above each panel [175].

4.1.3. Deposition

The activity deposited on the Earth's surface is quantified as deposition density and measured in terms of activity per unit area, usually expressed in Bq/m^2. When the deposition is terrestrial, it is usually referred to as ground 'contamination'.

Oceanic deposition

The deposition of ^{137}Cs onto the ocean was studied using different models (see Fig. 4.3).

It is difficult to produce an accurate estimate of the amount of ^{137}Cs released to the atmosphere which was deposited on the ocean surface [186]. As a reference, the global pre-accident deposition of ^{137}Cs as of 1970 is estimated at 290 ± 30 PBq and the typical (background) level of ^{137}Cs in the North Pacific Ocean was approximately 69 PBq [187, 188].

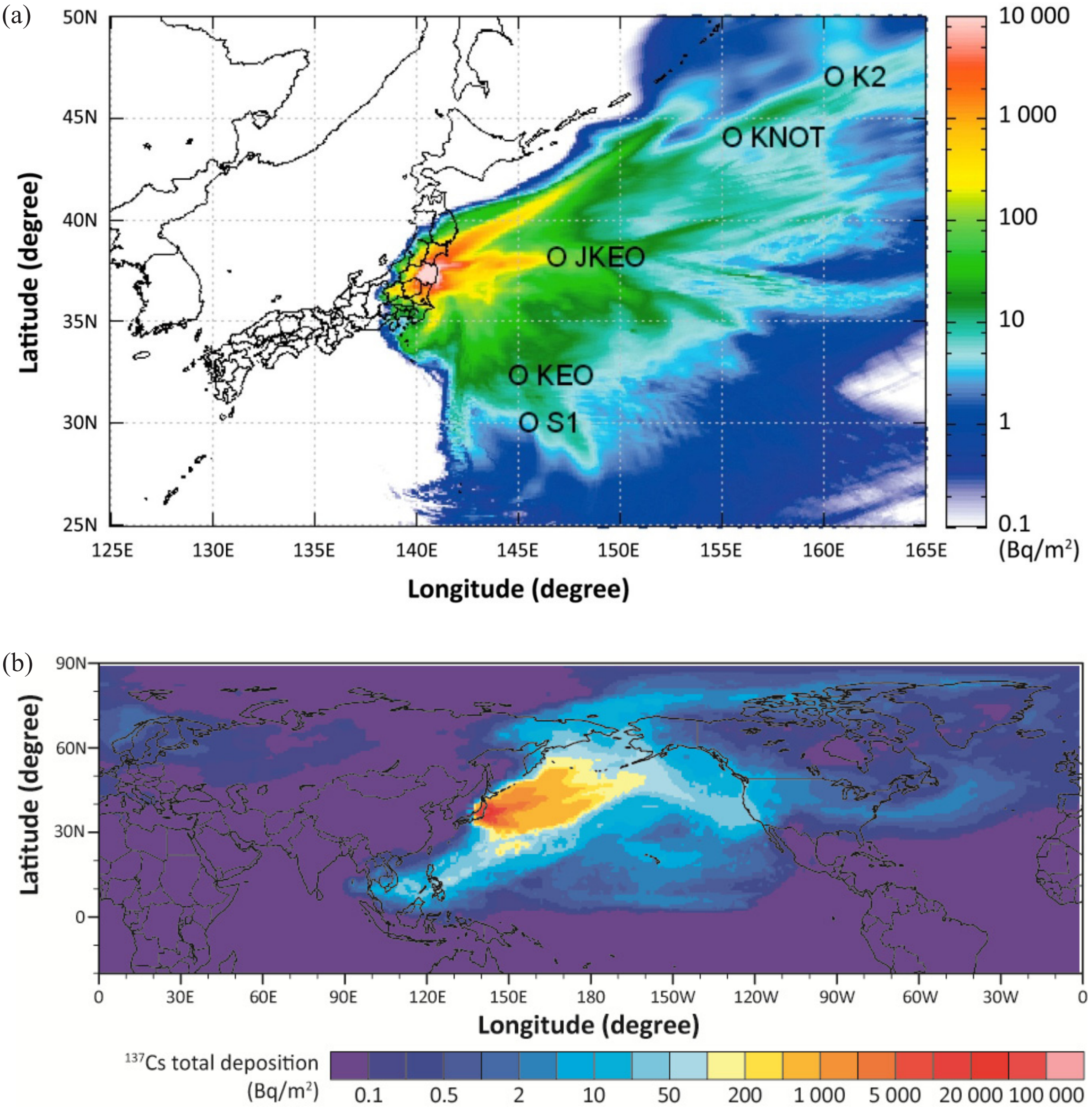


FIG. 4.3. Various models have been used to estimate the oceanic deposition density of ^{137}Cs (the units used are Bq/m^2). (a) Modelling the cumulative aeolian input through 1 April 2011 [185]; and (b) an example of the ensemble averaged ^{137}Cs deposition (11–31 March 2011) [175].

Terrestrial deposition

While most atmospheric releases were dispersed eastward, the releases that took place on 12, 14 and 15 March were blown over land, and relevant radionuclides, notably ^{131}I, ^{134}Cs and ^{137}Cs were deposited on the ground. The deposition patterns varied greatly, being influenced strongly by rain, snowfall and other local or regional conditions, such as topography and land use. Another factor that influenced the pattern of deposition in the terrestrial environment was the different physical and chemical characteristics of iodine and caesium.

The largest long lived deposits of ^{137}Cs were found to the north-west of the Fukushima Daiichi NPP, where the total deposition of ^{137}Cs on the land surface of Japan was estimated to have been around 2–3 PBq [188]. The deposition density decreases with time through physical and environmental decay. Caesium can move relatively easily through the environment owing to the solubility of its compounds. Weathering effects, such as wind and rain, and other environmental effects can reduce the presence of caesium in the environment. All these effects reduce the presence of ^{137}Cs in a time shorter than its half-life. In many affected areas, the presence of ^{137}Cs has been further reduced by cleanup and other remediation efforts.

Figure 4.4 presents detailed maps of the aerially measured ambient dose equivalent to the north-west of the site of the accident and its variation with time (see also Fig. 4.2 (c)).

The presence of ^{137}Cs from the accident in the terrestrial environment can result in protracted exposures of individuals, in addition to the exposures they normally incur from natural background levels of radiation. There is a global background level of deposition density of ^{137}Cs, attributable mainly to fallout from past nuclear testing. The background global levels were estimated by UNSCEAR to have been as high as approximately 4000 Bq/m^2, during the mid-1960s, at latitude 40^o–50^o in the Northern Hemisphere; the lowest global values at that time were estimated to have been around a few hundred Bq/m^2 at latitude 60^o–70^o in the southern hemisphere [190]. A number of studies analysed the influence of local conditions and concluded that the accumulated background deposition could have been around, or even higher than, 10 000 Bq/m^2 (e.g. see Ref. [187]). The global deposition levels have decayed since the 1960s. For 2000, the highest value was estimated by UNSCEAR to be around 2000 Bq/m^2 [190].

In areas north-west of the Fukushima Daiichi NPP, significantly higher levels of ^{137}Cs deposition density were measured. Presented by order of magnitude, the levels at the most affected areas were of the order of 10 000 000 Bq/m^2 and many areas had levels of around 1 000 000 Bq/m^2. The distribution of deposits for the whole affected area of Fukushima Prefecture is inhomogeneous, and the levels immediately outside the most affected areas in Fukushima Prefecture were around 10 000 Bq/m^2. While some other regions of Japan show elevated deposition levels, the levels attributable to the accident in most of Japan were generally lower than around 1000 Bq/m^2 [191, 192].

The highest levels of deposited ^{131}I exceeded 3 000 000 Bq/m^2 immediately after the accident but, owing to the short half-life of ^{131}I, the levels decreased rapidly and are no longer measurable.

4.1.4. Consumer products

In the affected areas, radionuclides, such as ^{131}I, ^{134}Cs and ^{137}Cs, were found in some consumer products and other items in daily use by individuals and households, such as food, drinking water and some non-edible products.

Restrictions were established after the accident, on 21 March, by the Japanese authorities to prevent the consumption of drinking water and food containing radionuclides at levels that were higher than provisional regulation values (see Section 3).

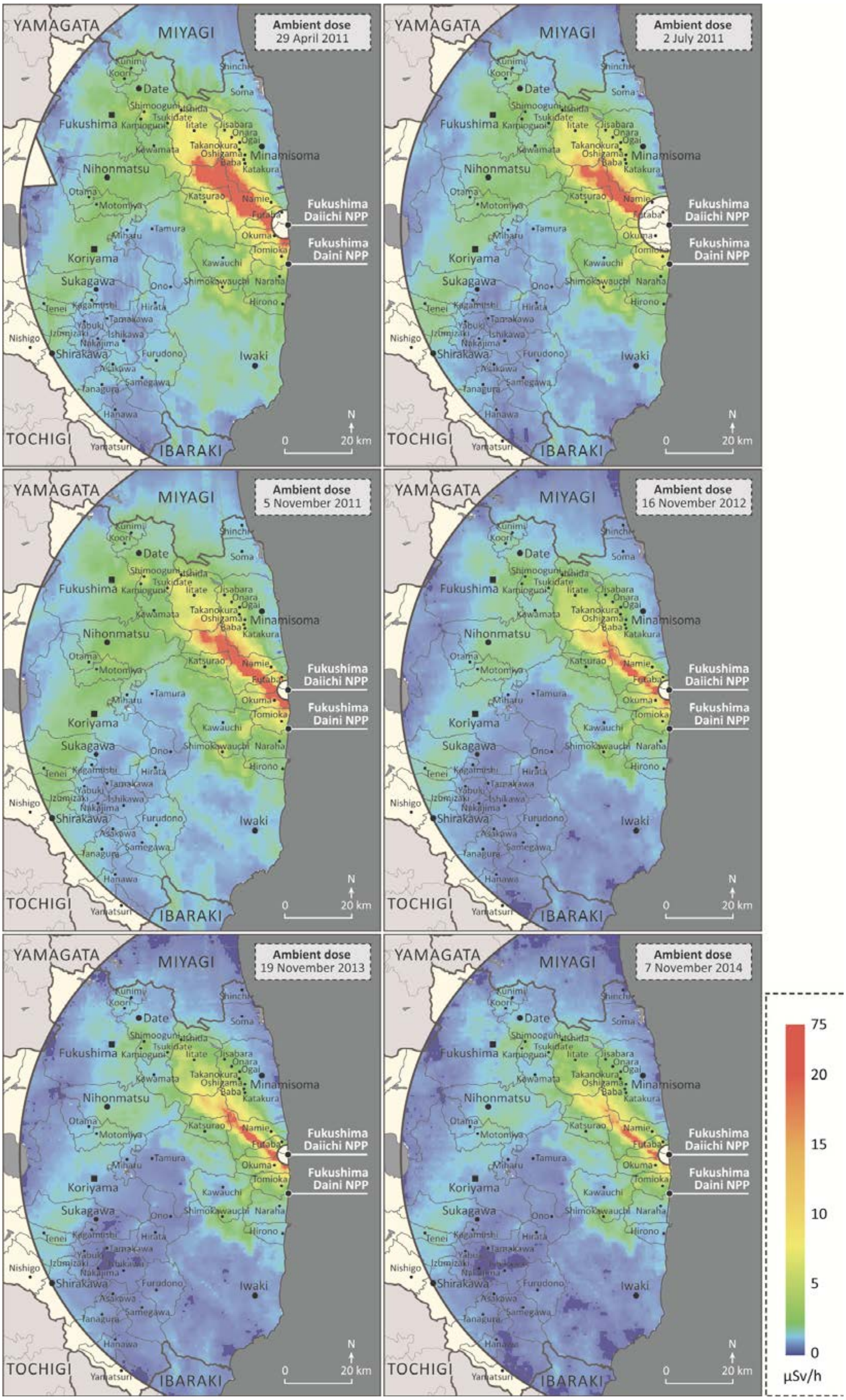
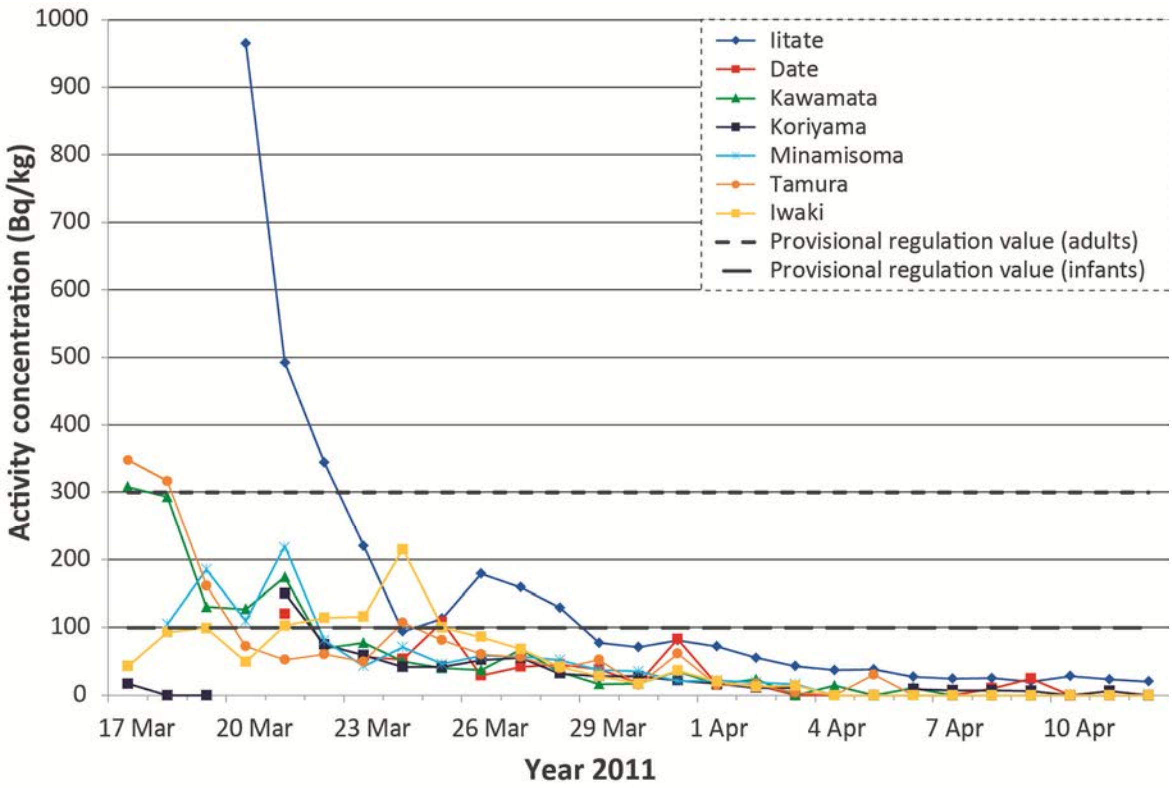


FIG. 4.4. Measured aerial ambient dose equivalent rate (in µSv/h) resulting from deposits from the releases that spread in areas to the north-west of the plant [189].

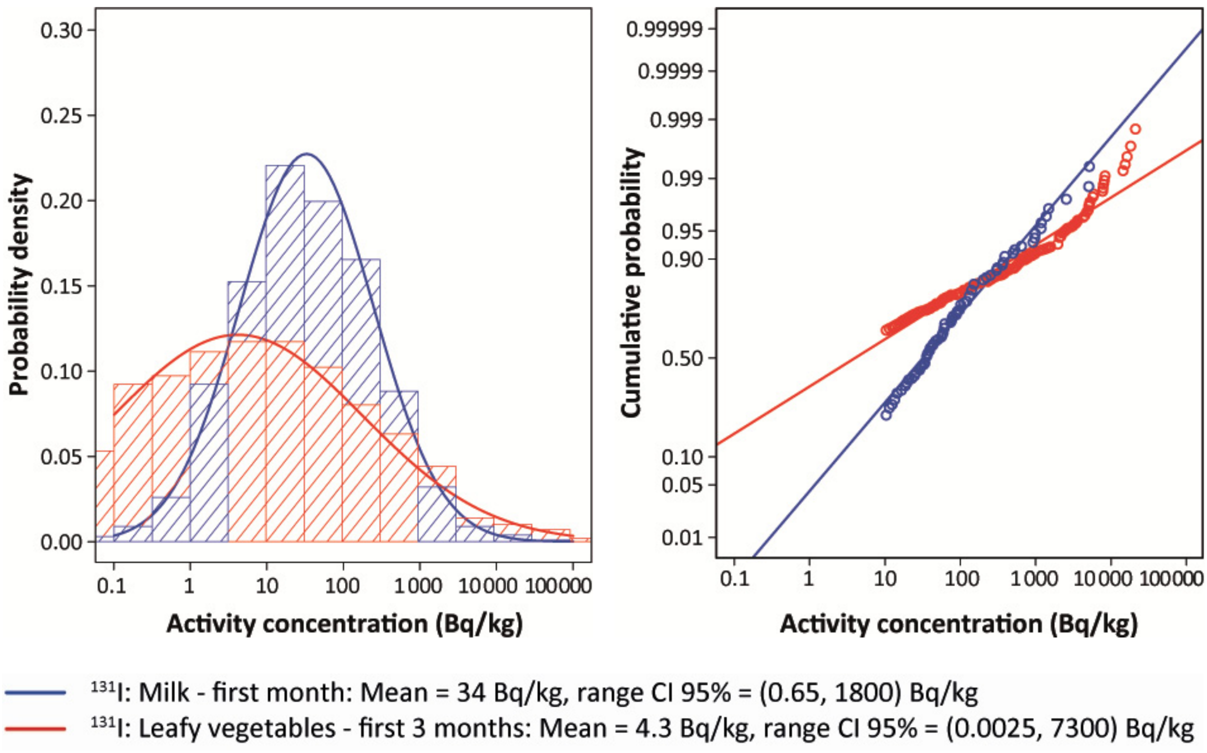
WHO guidance values for permissible levels of radionuclides in drinking water are intended for normal circumstances (see Box 4.1). After April 2012, all drinking water in Japan was below the WHO guidance values [193].

With rare exceptions, the levels of radionuclides in food available on the market did not exceed those established in the Codex Alimentarius, which are applicable to international trade (see Box 4.1). There were cases where higher levels of radionuclides were found in uncultivated foods, such as wild boar meat, wild mushrooms and wild plants, including ferns [194]. Eating uncultivated food is uncommon in Japan. Wild plants are mostly eaten for a limited period in the spring by a limited number of people. Direct sales of wild mushrooms and plants by farmers are very rare. Cultivated mushrooms are available in the market if the levels of activity concentration are under the regulated values.

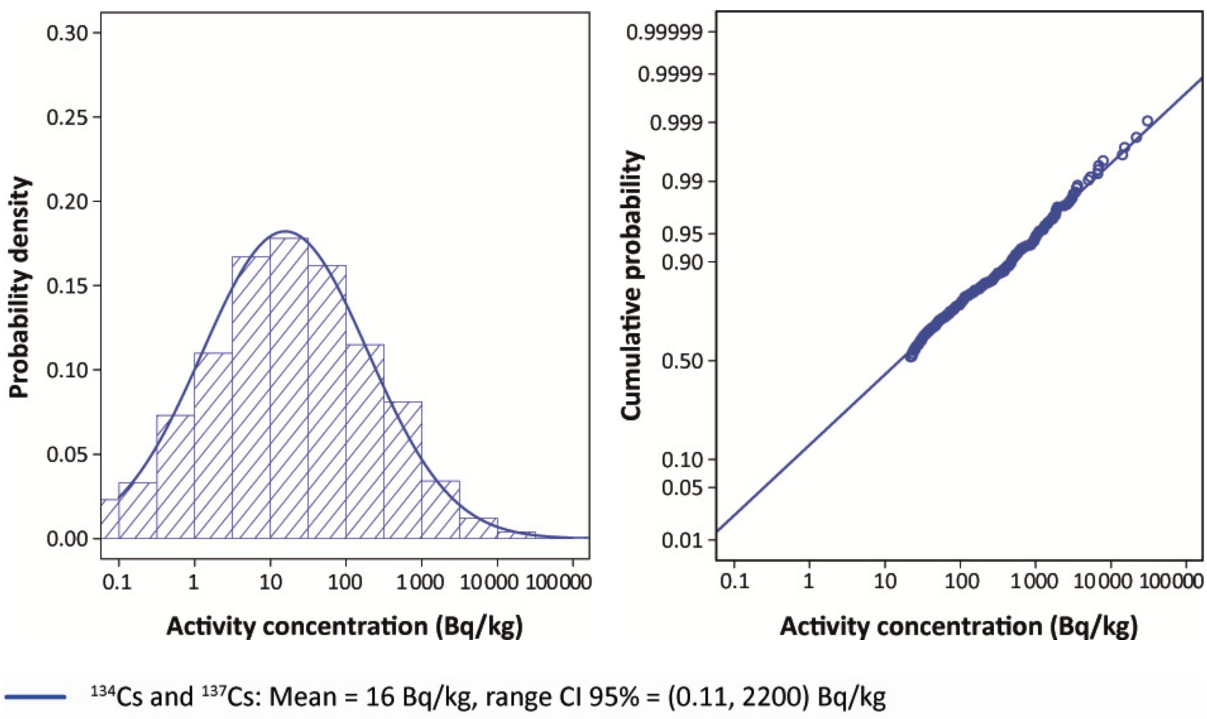
Some examples of activity concentration in drinking water and specific activity in food are presented in Fig. 4.5. The time evolution activity concentration of ^{131}I measured in drinking water supplies is illustrated for various locations in Fukushima Prefecture compared with the levels established in the provisional regulations issued by the Japanese authorities [195]. The log-normal probability density and cumulative probability distributions were assessed for the ^{131}I specific activity in milk during the first month after the accident and in leafy vegetables in the first three months after the accident. For ^{134}Cs and ^{137}Cs specific activity in mushrooms (including mainly cultivated mushrooms in the open air), they were assessed during the 12 months after the accident. These assessments, which are based on the statistical analysis of data collected by FAO [151], illustrate a likelihood of around 90% that values were below the Codex Alimentarius level of 1000 Bq/kg (the level established by the Japanese authorities was originally 500 Bq/kg and was then reduced to 100 Bq/kg [193]). This conservative approach created difficulties for producers and consumers.



(a)



(b)



(c)

FIG. 4.5. Some examples of radioactivity in drinking water and food. (a) Time evolution activity concentration of ^{131}I measured in drinking water supplies in various locations of Fukushima Prefecture [195]. (b) Log-normal probability distribution of ^{131}I activity concentration in milk in the first month after the accident and in leafy vegetables in the first three months after the accident. (c) Log-normal probability distribution of ^{134}Cs and ^{137}Cs activity concentration in mushrooms during the 12 months after the accident [151]. (Figures 4.5(b) and 4.5(c) present the normalized idealized probability density distribution (see Box 4.6) and the cumulative probability distribution; a nominal detection limit of 10 Bq/kg was used in the activity concentration in food.)

4.2. PROTECTING PEOPLE AGAINST RADIATION EXPOSURE

Following the accident, the Japanese authorities applied conservative reference levels of dose included in the recent ICRP recommendations[93]. The application of some of the protective measures and actions proved to be difficult for the implementing authorities and very demanding for the people affected.

There were some differences between the national and international criteria and guidance for controlling drinking water, food and non-edible consumer products in the longer term aftermath of the accident, once the emergency phase had passed.

People were exposed to radiation attributable to the accident through a number of different routes, known as exposure pathways. These are discussed in Box 4.7. Radiation doses incurred by people were estimated by modelling and/or environmental and personal measurements through the various exposure pathways. These estimates and measurements were then used for restricting exposure and ensuring the protection of people.

4.2.1 Restriction of public exposure

The version of the Basic Safety Standards (BSS) applicable at the time of the accident had been issued in 1996 [137] and was based on the ICRP recommendations issued in 1990 [196]. It included requirements on intervention levels in the case of accidents, considering expected projected doses and potential reductions of avertable doses. At the time of the accident, the 1996 BSS were being revised to reflect the ICRP recommendations that had been issued in 2007 [129] (see Box 4.8). These recommendations contained a different approach to dealing with emergencies, particularly reviewing the concept of intervention levels, which had been designed as criteria for individual protective actions, and introducing the concept of reference levels that were intended to be used for deciding protection strategies (on the understanding that generic criteria would be introduced in safety standards for dealing with individual protective actions).

The 2007 ICRP recommendations provided a framework for reference levels, with examples for all exposure situations, including emergency situations. As an example for the highest planned residual dose from a radiological emergency, they recommended reference levels that could be greater than 20 mSv, either acute or annual, but not more than 100 mSv. They also recommended that consideration should be given to reducing doses, increasing efforts should be made to reduce doses as they approach 100 mSv, individuals should receive information on radiation risk and on measures to reduce doses, and assessment of individual doses should be undertaken. The Japanese regulatory body, NISA, chose to apply the lower reference level of 20 mSv/year as a reference level for public protection.

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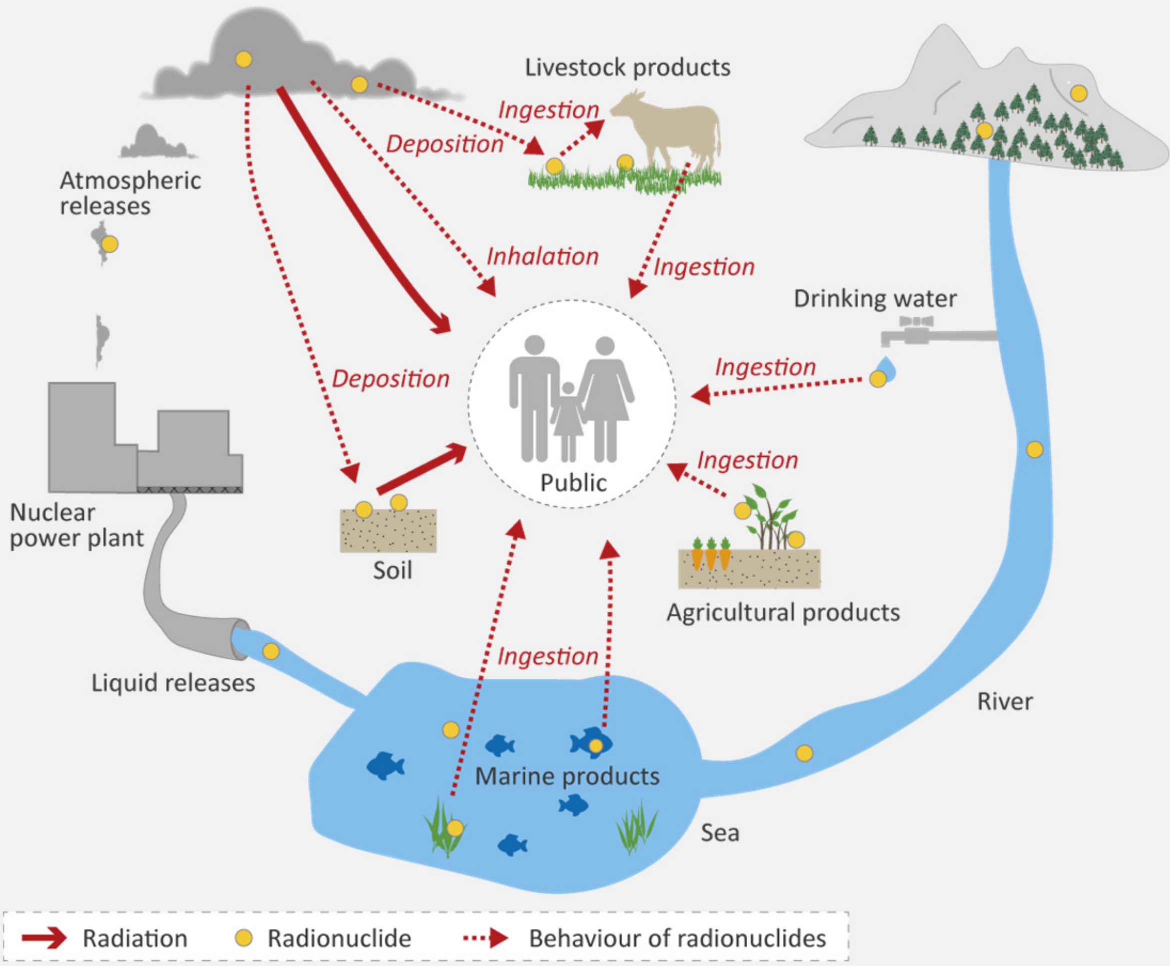
[93] International recommendations on radiation protection are issued by the ICRP. These recommendations are taken into account in the establishment of international safety standards, including radiation protection standards (the International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources (the Basic Safety Standards, or BSS)), which were developed and established by several international organizations and issued under the aegis of the IAEA. The BSS are used worldwide in the development of national regulations for the protection of people and the environment from the potential detrimental effects of exposure to ionizing radiation. The 2007 ICRP recommendations provided a revised framework for radiation protection. These included introducing reference levels for protection strategies. At the time of the accident, the BSS were being revised, inter alia, to take account of these recommendations.

Box 4.7. Exposure pathways

Exposure pathways are courses, sequences of changes, or events which constitute the progression by which radioactive substances move through the environment and eventually make people vulnerable to incurring radiation doses. They are characterized by many aspects, including the process for the substances to reach the environment, the media in which the substances move from the source, the point of exposure where people are affected by radiation, the exposure routes describing how people are exposed to external radiation and how the radioactive substances may enter the body (e.g. by eating, drinking, via the skin) and the population that could be potentially exposed. The figure below gives a simplified description of the exposure pathways from the accident at the Fukushima Daiichi NPP.



Protection of children

The protection of children was a special concern for parents in areas affected by the accident. For protection purposes, the current ICRP recommendations use a detriment-adjusted risk coefficient for the whole population, including children, that is higher (by about 30%) than that for an adult population. This difference is reflected in the international radiation protection recommendations and standards.

Impact of radiation protection measures and actions taken to protect the public

Proper infrastructure for public facilities is essential for supporting measures to limit public exposure in the aftermath of a nuclear or radiological emergency [199]. The consequences of the earthquake, tsunami and accident had to be dealt with in a situation in which local infrastructure had collapsed.

Due to the earthquake and the tsunami, many public facilities, homes and businesses were destroyed or damaged; access to telephones and the Internet, supplies of electricity, gas, and drinking water, public transport, and the distribution of food, gasoline and heating oil were all severely disrupted. The outside temperature was low, it was raining and snowing, and heating was inadequate. This meant that many residents could not stay in the shelters for long periods without warm clothes and overcoats.

These difficult conditions affected the implementation of the protective measures required to protect people against radiation exposure. For example, people who were sheltered could not be decontaminated through washing because in most shelters water was rationed and reserved for drinking.

Box 4.8. Revising the Basic Safety Standards in effect at the time of the accident: Reference levels

The international safety standards for radiation protection in effect at the time of the accident were the 1996 International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, or 1996 BSS [137]. These standards required that the additional effective dose that individuals may receive from planned and regulated practices be limited to 1 mSv in a year (in special circumstances, an effective dose of up to 5 mSv could apply, provided that the average effective dose over five consecutive years does not exceed 1 mSv per year). The 1996 BSS underlined that these dose limits were not relevant for decisions on whether and how to undertake an intervention in case of accidents, when consideration had to be given to projected doses and potential reductions of avertable doses and eventual residual doses. The requirements of the 1996 BSS relating specifically to emergencies provided generic intervention levels at which intervention was expected to be undertaken in an emergency, such as sheltering, evacuation and thyroid blocking, and generic action levels for food.

In addition, the IAEA had, in 2002, issued safety standards with specific requirements on preparedness and response for a nuclear or radiological emergency [69], including dose criteria for the implementation of protective actions, such as sheltering, evacuation and iodine thyroid blocking. These standards established requirements for an adequate level of preparedness and response for a nuclear or radiological emergency with the aim of minimizing the consequences of an emergency if it were to occur (see Section 3 for more information).

At the time of the accident, the 1996 BSS were being reviewed, partly in the light of new general ICRP recommendations that had been issued in 2007 [129]. Just before the accident, the ICRP had issued specific recommendations on the application of its new recommendations for the protection of people in emergency exposure situations [127] and those living in long term contaminated areas after a nuclear accident or a radiation emergency [197].

The 2007 ICRP recommendations revised the approach to dealing with emergency exposure situations, including the concept of reference level to be used for protecting strategies. The recommended reference level was an effective dose (either acute or annual) that could be greater than 20 mSv but not higher than 100 mSv. This was to be used for generic criteria for dealing with individual protective actions in unusual, and often extreme, situations where actions taken to reduce exposures would be disruptive, with the understanding that an effective dose rising towards 100 mSv will almost always justify protective action. For stages in post-accident rehabilitation, the reference level could be greater than 1 mSv, but not more than 20 mSv. The new recommendations further emphasized that the chosen value for a reference level would depend upon the prevailing circumstances of the exposure under consideration.

The new approach was introduced in the revised BSS, issued in 2014 as IAEA Safety Standards Series No. GSR Part 3, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards [198].

Some protective actions were very difficult for the authorities and extremely demanding for the affected individuals and communities [200, 201]. Sheltering and evacuation were particularly disruptive for around 160 000 people who were isolated from their communities and had access to only limited supplies to meet their daily needs (Fig. 4.6(a)). People were eventually relocated, but their normal living conditions were seriously affected (Fig. 4.6(b)). Employment and participation in community activities were limited. Their prospects were uncertain and planning for the future was very difficult.

(a) (b)

FIG. 4.6. The initial evacuation led to crowded conditions in shelters. (a) A senior TEPCO executive apologizes to evacuees at an evacuation centre on 22 March 2011 (photograph courtesy of Koichi Nakamura/AP Images/picturedesk.com); (b) the normal living conditions of the people who were relocated were greatly affected (photograph courtesy of Dr Yujiro Kuroda/Fukushima Medical University).

People who had already suffered the consequences of the earthquake and tsunami were also subject to additional physical and psychological stress caused by their sheltering, evacuation and relocation. Restrictions on products for public consumption were important and necessary, but caused economic and reputational or social damage to local producers.

4.2.2 Restriction of occupational exposure, including exposure of emergency workers

Japan is a Party to the Radiation Protection Convention, 1960 (No. 115), adopted under the aegis of the ILO [164]. The Japanese regulations for occupational exposures were consistent with international recommendations and standards on occupational protection. These regulations established a dose limit for occupational exposure as an effective dose of 20 mSv per year, averaged over five years, and 50 mSv in any single year [137]. For emergency workers, "worker[s] who may be exposed in excess of occupational *dose limits* while performing actions to mitigate the consequences of an *emergency* for human health and *safety*, quality of life, property and the environment" [48], a limiting effective dose criterion of 100 mSv was in place. This criterion had to be temporarily increased by the Japanese authorities to a dose limit of 250 mSv for the emergency workers who were within 30 km of the Fukushima Daiichi NPP until 16 December 2011 (see Section 3.2).

The dose limit for occupational exposure in 'special circumstances', established by the international standards at the time of the accident (1996 BSS), was 100 mSv [137]. The upper level of the internationally recommended reference levels by the ICRP was also 100 mSv [129], although the recommendations indicate that, in exceptional situations, informed volunteer workers may receive doses above this level to save lives, prevent severe radiation induced health effects or prevent the development of catastrophic conditions. In setting the value of 250 mSv, the Japanese authorities took account of previous recommendations by the ICRP [196, 202] and the requirements in the IAEA safety standards, which suggested a guidance value of 500 mSv for persons engaged in emergency activities or in emergency operations aimed at preventing further worsening of a nuclear accident. The revised dose limit for emergency workers was implemented in the exemption ordinance of the Ministry of Health, Labour and Welfare (MHLW) three days after the declaration of the emergency by the authorities (14 March 2011). The exemption ordinance was abolished on 16 December 2011 [203].

4.3. RADIATION EXPOSURE

In the short term, the most significant contributors to the exposure of the public were: (1) external exposure from radionuclides in the plume and deposited on the ground; and (2) internal exposure of the thyroid gland, due to the intake of ^{131}I, and internal exposure of other organs and tissues, mainly due to the intake of ^{134}Cs and ^{137}Cs. In the long term, the most important contributor to the exposure of the public will be external radiation from the deposited ^{137}Cs.

The early assessments of radiation doses used environmental monitoring and dose estimation models, resulting in some overestimations. For the estimates in this report, personal monitoring data provided by the local authorities were also included to provide more robust information on the actual individual doses incurred and their distribution. These estimates indicate that the effective doses incurred by members of the public were low and generally comparable with the range of effective doses incurred due to global levels of natural background radiation.

In the aftermath of a nuclear accident involving releases of ^{131}I and its intake by children, the uptake and subsequent doses to their thyroid glands are a particular concern. Following the Fukushima Daiichi accident, the reported thyroid equivalent doses of children were low because their intake of ^{131}I was limited, partly due to restrictions placed on drinking water and food, including leafy vegetables and fresh milk. There are uncertainties concerning the iodine intakes immediately following the accident due to the scarcity of reliable personal radiation monitoring data for this period.

By December 2011, around 23 000 emergency workers had been involved in the emergency operations. The effective doses incurred by most of them were below the occupational dose limits in Japan. Of this number, 174 exceeded the original criterion for emergency workers and 6 emergency workers exceeded the temporarily revised effective dose criterion in an emergency established by the Japanese authority. Some shortcomings occurred in the implementation of occupational radiation protection requirements, including during the early monitoring and recording of radiation doses of emergency workers, in the availability and use of some protective equipment and in associated training.

The dose estimates in this report used as a basis international dose estimates by WHO and UNSCEAR, which are summarized in Box 4.9. This report also benefited from the availability of additional data, particularly from the Fukushima Health Management Survey and data on direct measurements of dose to people and radiation in the environment. These data were provided by experts, institutions, the local authorities and the Government of Japan, as well as by TEPCO, and were subjected to a statistical analysis.

The various estimates differed because they were carried out at different times and with different methodologies. While WHO estimates were generally higher than those of UNSCEAR, this was primarily because they were early dose projections based on very limited data following the accident. The dose estimates for members of the public by WHO and UNSCEAR were constrained by limited availability of direct radiation measurements of individual doses incurred by people and were mainly made using dose assessment models based on environmental conditions. Although the differences make a detailed comparison difficult, the estimates in this report and those of WHO and UNSCEAR are largely consistent in showing that doses generally fell below reference levels established in international recommendations and standards.

Box 4.9. *Dose estimates by WHO in 2012 [146] and UNSCEAR in 2014 [148]*

In 2012, the World Health Organization (WHO) issued an early evaluation of radiation exposure from the accident, which gave an initial estimate of radiation doses to characteristic members of the public using modelling techniques applied to information made publicly available by government institutions and collected up to September 2011. At that time, the data necessary for a full evaluation were either not available or not sufficient. A number of cautious assumptions were used that may have resulted in some doses being overestimated. For example, cautious assumptions were used to minimize the possibility of underestimating eventual health risks regarding protective actions and the consumption of food. Nevertheless, the evaluation showed that the total effective dose typically received by individual members of the public in two locations of relatively high exposure in Fukushima Prefecture during the first year after the accident was within an effective dose band of 10–50 mSv. In these most affected locations, external exposure was the major contributor to the effective dose. In the rest of Fukushima Prefecture, the effective dose was estimated to be within an effective dose band of 1–10 mSv. Effective doses in most of Japan were estimated to be within an effective dose band of 0.1–1 mSv, while in the rest of the world, all the effective doses were below 0.01 mSv and usually far below this level.

In 2014, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) issued a report on the accident that included assessed doses to workers and members of the public. Estimates of external effective doses to members of the public were based on the information available on ^{137}Cs deposition density in different areas as a function of time, and the estimated location and movement patterns of the population. UNSCEAR estimates indicated that, in the evacuated areas with the highest average estimates, the effective dose received by adults before and during the evacuation was, on average, less than 10 mSv, and about half of that level for those evacuated early. Adults living in Fukushima City were estimated to have received, on average, an effective dose of about 4 mSv in the first year following the accident; estimated effective doses for one year old infants were about twice as high.

Those living in other areas within Fukushima Prefecture and in neighbouring prefectures were estimated to have received comparable or lower effective doses; even lower effective doses were estimated to have been received elsewhere in Japan. Lifetime effective doses attributable to the accident that, on average, could be received by those continuing to live in Fukushima Prefecture have been estimated by UNSCEAR to be just over 10 mSv. Radiation exposures in neighbouring States and the rest of the world resulting from the accident were far below those received in Japan; the effective doses were less than 0.01 mSv. However, UNSCEAR emphasized that there was considerable variation among individuals around this value, depending on their location and what food they consumed.

Note: As indicated in Box 4.3, the global natural background doses reported by UNSCEAR are an annual average dose of 2.4 mSv (which implies a total accumulated lifetime dose of around 170 mSv), with a typical range of 1–13 mSv, while sizeable population groups receive natural background doses of 10–20 mSv.

4.3.1 Public exposures

External exposure

The initial approach to estimating the effective doses incurred by members of the public due to external exposure was mainly based on data from environmental measurements of ambient dose equivalent rates and on calculations and surveys of location and personal behaviour. The data used encompassed extensive measurements of ambient dose equivalent, including the use of car-borne instrumentation.

The NIRS estimated the effective doses due to external exposures incurred by respondents to the Fukushima Health Management Survey questionnaires in the four months following the nuclear accident [204]. The estimations were based on the declared movements of people and the relevant radiation levels in the local environments.

A number of estimates of the individual effective doses due to external exposure in the first four months have been published [205–208]. For example, in the Soso area[94] (which includes the ‘evacuation zone’ and ‘Deliberate Evacuation Area’), these doses were below 5 mSv for 98.7% of residents (with a maximum effective dose of 25 mSv). In Fukushima Prefecture as a whole, including the evacuation zone and Deliberate Evacuation Area, the doses were below 3 mSv for 99.4% of the residents surveyed [208].

A statistical analysis was undertaken in this report of individual effective doses due to external radiation in various municipalities of Fukushima Prefecture that had been estimated by the NIRS using the Fukushima Health Management Survey data for the period 11 March–11 July 2011 (the effective dose due to external exposure to natural background radiation was excluded). The results of this analysis are presented in Fig. 4.7 for municipalities located in the area within the 20 km radius and for municipalities outside this area. This figure illustrates that external doses in the first four months were, on average, lower among the populations in the 20 km zone than those from locations outside this area, as a consequence of the early evacuation of this zone. The results within the 20 km zone tend to show wider distributions than those for locations outside the zone. This is due to the evacuation of members of the same community to different locations and often further movements leading to differences in the doses received. This complicated pattern was modelled by the NIRS using 18 evacuation scenarios.

There are uncertainties associated with the use of interviews with residents, environmental measurements and dose estimation models for assessing public doses. Personal radiation monitoring of members of the public is therefore vital for a reliable reconstruction of radiation doses.

The more important corroboration of individual doses from external radiation was provided by the data on individual monitoring using personal dosimeters. When personal monitoring data became available, they allowed comparison between the two different approaches, using assumptions about people’s habits and models, to estimate the effective dose incurred versus monitoring the actual personal dose equivalent incurred[95].

The results indicated that the doses actually incurred, as measured by personal monitors, were generally lower than the estimated doses from questionnaires and modelling. An example of this comparison, which was carried out by a local government, is presented in Fig. 4.8. It shows that modelled doses are usually overestimations compared with actually incurred doses (this was also observed during the dose assessments in the aftermath of the Chernobyl accident [169]).

The large amount of information provided by Japan to the IAEA included data on personal dose equivalents and results from whole body counting measurements.

This information had been recorded at different times, over different periods, using different measurement techniques, and measurements were carried out in many, but not all, affected areas. What these data have in common is the fact that all personal dose equivalents are low (the committed effective doses estimated from whole body counting were negligible, see below), resulting in effective dose levels that are comparable with typical background effective dose levels.

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[94] An area in the eastern part of Fukushima Prefecture, comprising Soma City, Minamisoma City, Hirono Town, Naraha Town, Tomioka Town, Kawauchi Village, Okuma Town, Futaba Town, Katsurao Village, Namie Town, Shinti Town and Iitate Village, many of which were within the designated ‘evacuation zone’ or ‘Deliberate Evacuation Area’.

[95] The quantity used for personal monitoring, the personal dose equivalent, is a proxy of the quantity effective dose.

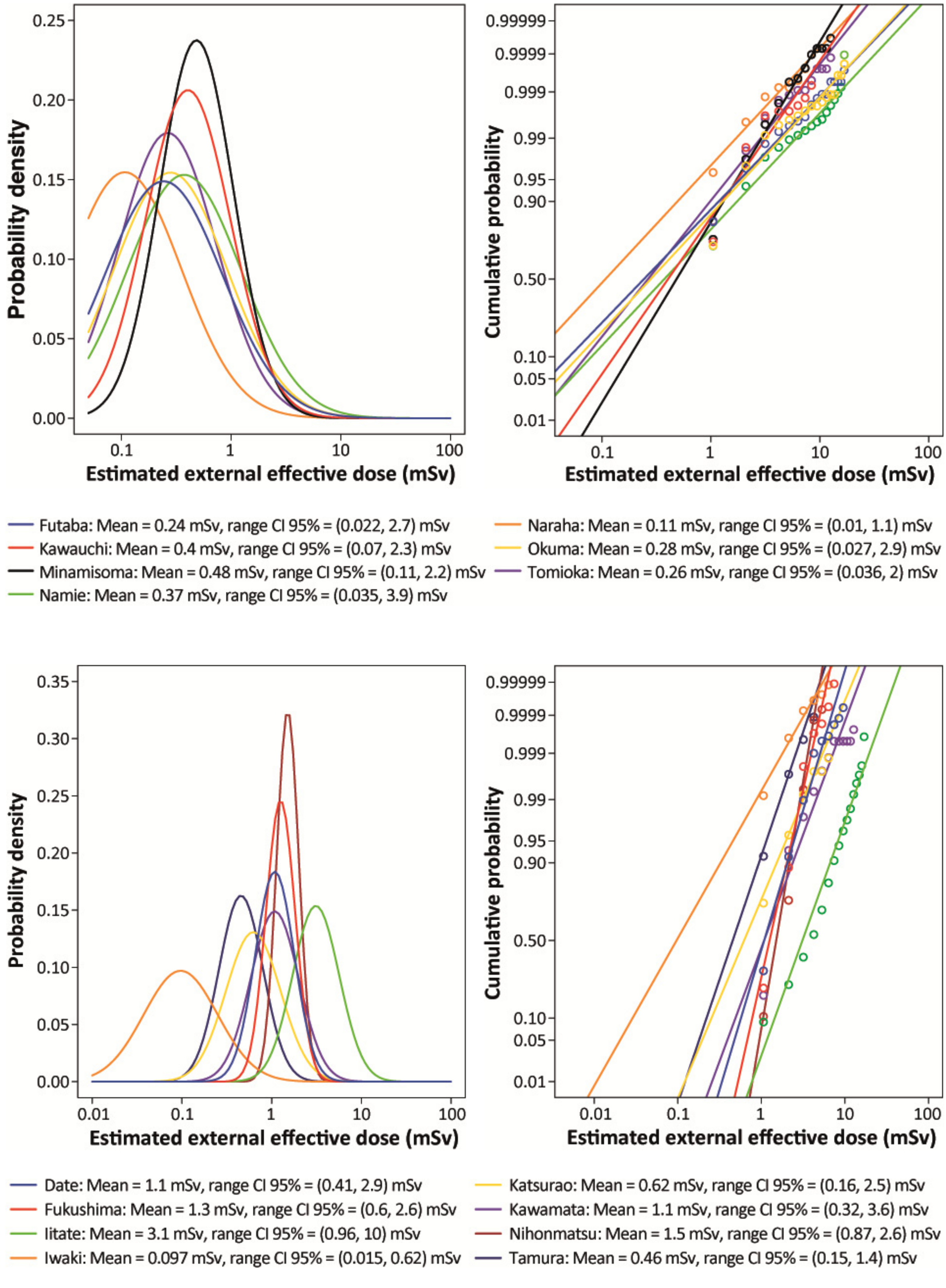


FIG. 4.7. Log-normal normalized idealized probability density and cumulative probability distributions of the estimated external effective doses in various cities, towns and villages of Fukushima Prefecture for the four months following the accident on the basis of Fukushima Health Management Survey data. The upper part of the figure presents the analysis for places located in the area within the 20 km radius (see Section 3) and the lower part of the figure for places outside this area. The legend under the plots indicates the mean doses and the 95% confidence interval for these places. In the original data, all doses below 1 mSv were accumulated in the 1 mSv bin.

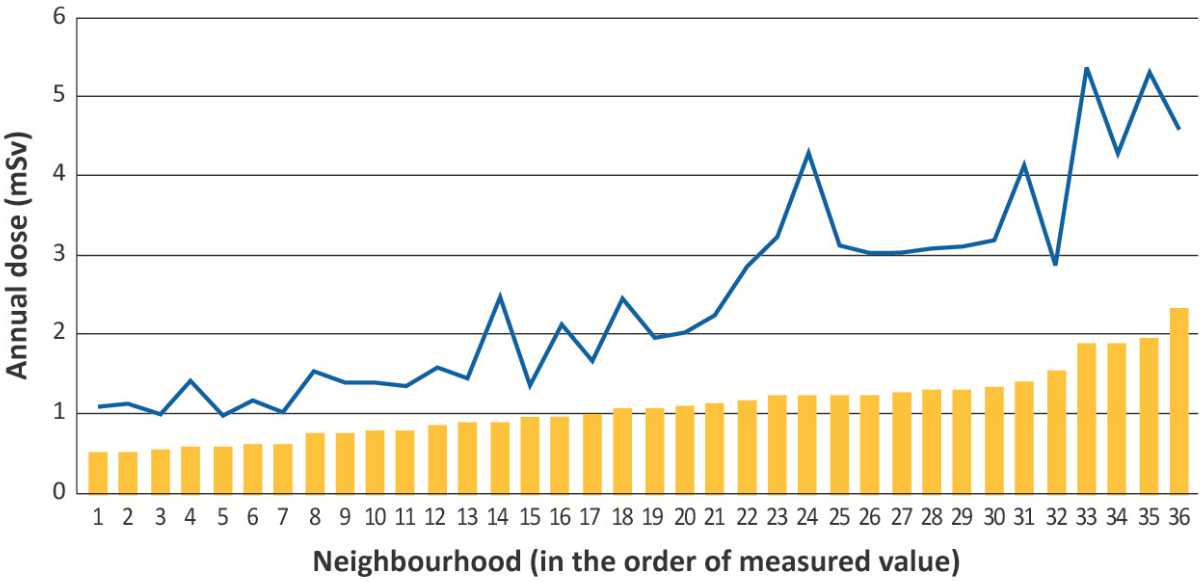


FIG. 4.8. Comparison of external individual dose estimates with measurements for a representative affected city between July 2012 and June 2013. The effective doses are assessed by estimation (line), assuming indoor occupancy and shielding for 16 h, outdoors for 8 h, and by personal monitoring (bar) of personal dose equivalent, in various neighbourhoods of the city (numerated) [209].

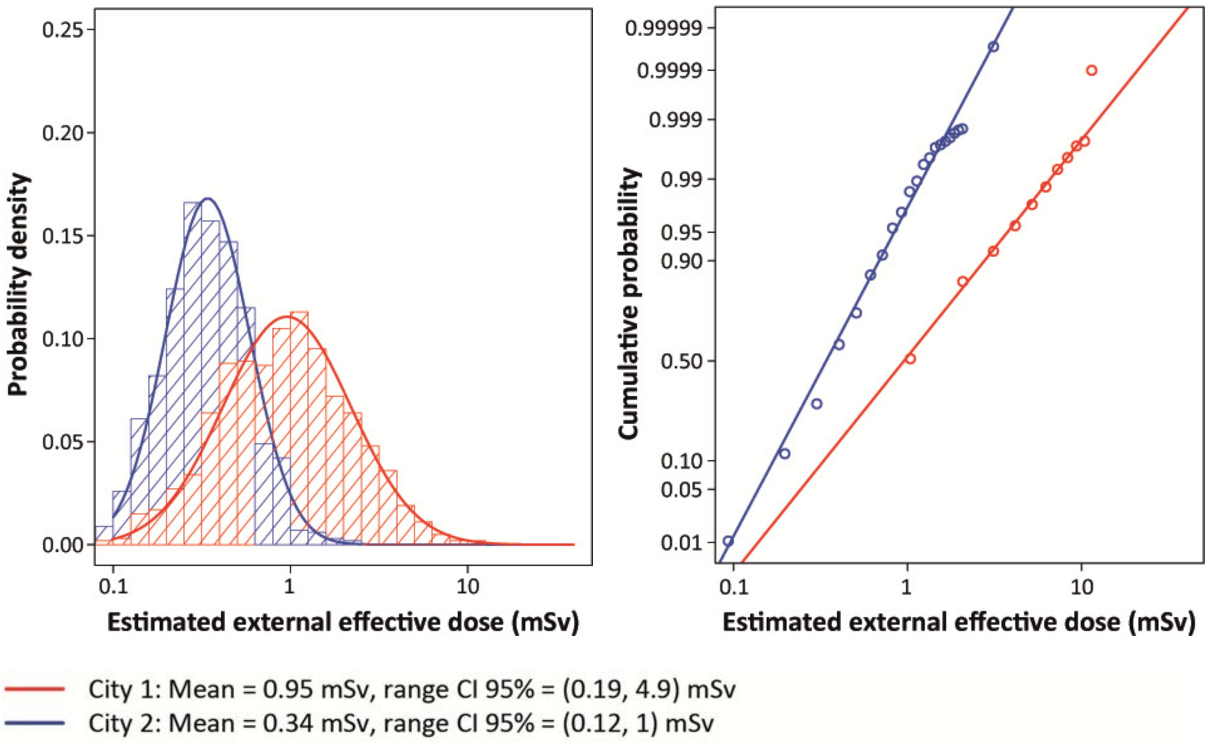


FIG. 4.9. Probability distribution of monitored personal dose equivalents of members of the public during 2011 provided by the Government of Japan for two municipalities in the affected area for which annualized data were available. For city 1 the normalized idealized probability density distribution is illustrated in red; for city 2 the normalized idealized probability density is illustrated in blue; for both cities the cumulative probability distribution is illustrated (see Box 4.6). The distribution shows that personal dose equivalents are low, with averages below 1 mSv per year, providing 95% confidence that individuals who incurred effective doses in those municipalities sustained doses below 5 mSv.

Figure 4.9 illustrates this analysis for two municipalities in the affected areas for which annualized information was available. The analysis reconfirmed that the annual personal dose equivalents are low, with average effective doses below 1 mSv per year, providing 95% confidence that people incurred effective doses below 5 mSv.

Internal exposure

Measurements of intake of radionuclides using whole body counting were made by the NIRS, the JAEA and other organizations in Japan.

After the accident, monitoring was carried out on more than 200 000 residents in various locations within Fukushima Prefecture. The levels were generally lower than the very low detection limits of the whole body counters, indicating little or no intake of radionuclides into the body. As a result, it was neither possible nor necessary to undertake detailed statistical analysis of these data.

Where it was possible to convert measured intakes to effective dose, making assumptions about the timing and nature of the intake, the vast majority of estimates of the committed effective dose were less than 1 mSv [210]. The estimated effective dose commitment from whole body counting measurements of ^{134}Cs and ^{137}Cs was reported to be lower than around 1 mSv in 99% of the residents [206].

Many whole body counting measurements were carried out several months after the accident [211, 212] and are therefore often only applicable to ^{134}Cs and ^{137}Cs, due to the short half-life of ^{131}I. Given the importance of intakes of ^{131}I through both inhalation and ingestion in the first month following the accident, this made judgements on internal exposure difficult. However, it was possible to detect ^{131}I in measurements of evacuees and short term visitors to Fukushima Prefecture carried out at Nagasaki University [213]. The highest estimated thyroid absorbed dose was 20 mGy (i.e. a thyroid equivalent dose of 20 mSv), with a corresponding effective dose of around 1 mSv.

The internal doses incurred in the initial period were dependent on whether people ate locally produced food or food from elsewhere, or drank tap water, during the first few days, before restrictions were fully put in place. Market basket surveys suggested that exposures from the consumption of milk, food and water were very low, as locally produced milk and food products were not distributed to shelters and only bottled water was used for drinking and preparing baby formula.

Exposure from the consumption of vegetables was low as very few, if any, locally produced vegetables grown outdoors were being eaten; it was early spring, before the growing season. Effectively, the only locally produced vegetables consumed were those grown in greenhouses, which were not contaminated.

Doses to the thyroid gland in children

In the aftermath of a nuclear accident involving substantial releases of ^{131}I, doses to the thyroid gland in children are an important public health concern. The main potential pathway for thyroid doses in children is usually the intake of milk containing ^{131}I.

However, the typical intake of ^{131}I via cow's milk was very low following the accident, owing to a number of factors. Dairy practices in Japan, such as generally sheltering cattle, prevented the ingestion of ^{131}I by dairy cows. The intake of ^{131}I via milk was also limited by the relatively low contribution of milk to the diet of infants and by the strict restrictions on the consumption of milk imposed by the authorities following the accident. While there were alternative ^{131}I ingestion pathways such as the consumption of leafy vegetables and drinking water, especially in the very early period following the release, the prompt restrictions on drinking water and food limited the intake via these pathways.

As a result of these factors, the intake of ^{131}I by children is likely to have been low and mainly attributable to inhalation. However, there were uncertainties associated with the estimates of ^{131}I intakes and thyroid equivalent doses in children in the first few days following the accident.

Thyroid equivalent doses to children were estimated by monitoring levels of external radiation from ^{131}I activity in the gland. These levels were measured on the skin, near the thyroid, of children from areas where thyroid doses were predicted to be high. A limited number of these direct measurements were reported for the weeks following the accident. The results of one study, in which 1080 measurements were made on children aged 1–15 years in Iwaki City, Kawamata Town and Iitate Village in the period 26–30 March 2011, are summarized in Fig. 4.10 [214].

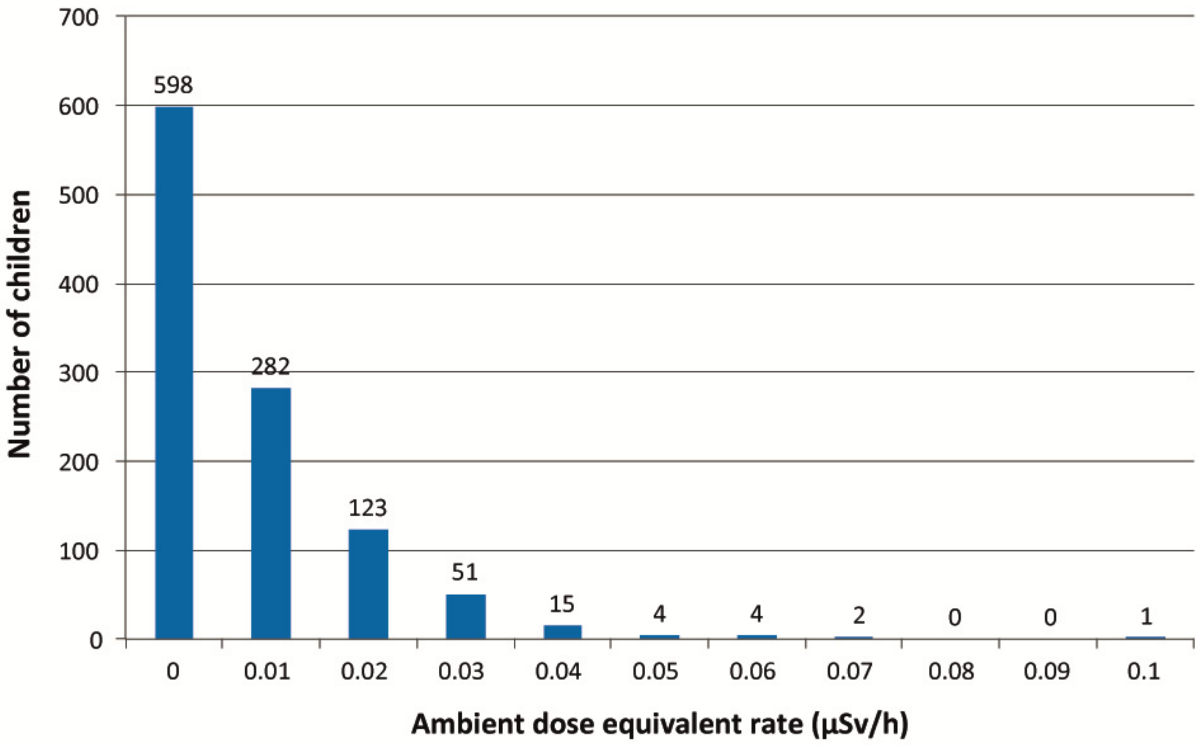


FIG. 4.10. Distribution of net value of measured dose rate in thyroid gland estimated by subtracting the background value from the reading value [214], i.e. the net ambient dose equivalent rates at the thyroid gland, in 1080 children aged 0–15 years. For 99% of the children tested, the ambient dose equivalent rate measured near the thyroid was 0.000 04 mSv per hour or less, corresponding to a thyroid equivalent dose of approximately 20 mSv or less.

The highest ambient dose equivalent rate measured near the thyroid of one year old children was 0.0001 mSv per hour, which would be consistent with an absorbed dose to the thyroid of approximately 50 mGy (a thyroid equivalent dose of 50 mSv). It was reported that thyroid equivalent doses, determined in March 2011 using an NaI (Tl) scintillation survey meter in children in the evacuation zone and ‘Deliberate Evacuation Area’, were lower than around 10 mSv in 95.7% of children (with a maximum of 43 mSv) [214]. It is likely that all doses were lower than the generic optimized intervention value for iodine prophylaxis of 100 mGy of avertable committed absorbed dose to the thyroid due to radioiodine established in the 1996 BSS [137]. They were also lower than the projected dose of 50 mSv in the first seven days for iodine thyroid blocking established in the revised BSS [198] as generic criteria for protective actions and other response actions in emergency exposure situations to reduce the risk of stochastic effects. In comparison, the absorbed doses by thyroid of children following the Chernobyl accident ranged up to several thousand mGy [169, 178], nearly 100 to 1000 times higher.

4.3.2 Occupational exposures

Following the accident, on-site emergency workers were immediately subjected to extremely harsh working conditions and very high radiation levels as they sought to stabilize the reactors. In the period from March 2011 to March 2012, 174 of the approximately 23 000 workers on the site exceeded the original effective dose criterion in an emergency of 100 mSv, six of whom exceeded the (temporarily revised) effective dose criterion in an emergency of 250 mSv. No workers exceeded an effective dose of 100 mSv in subsequent years. One worker[96] exceeded the occupational annual effective dose limit of 50 mSv in the period from April 2012 to March 2013 [203]. Figure 4.11 presents the comparison of effective doses incurred by emergency workers at the Fukushima Daiichi NPP between March 2011 and October 2014.

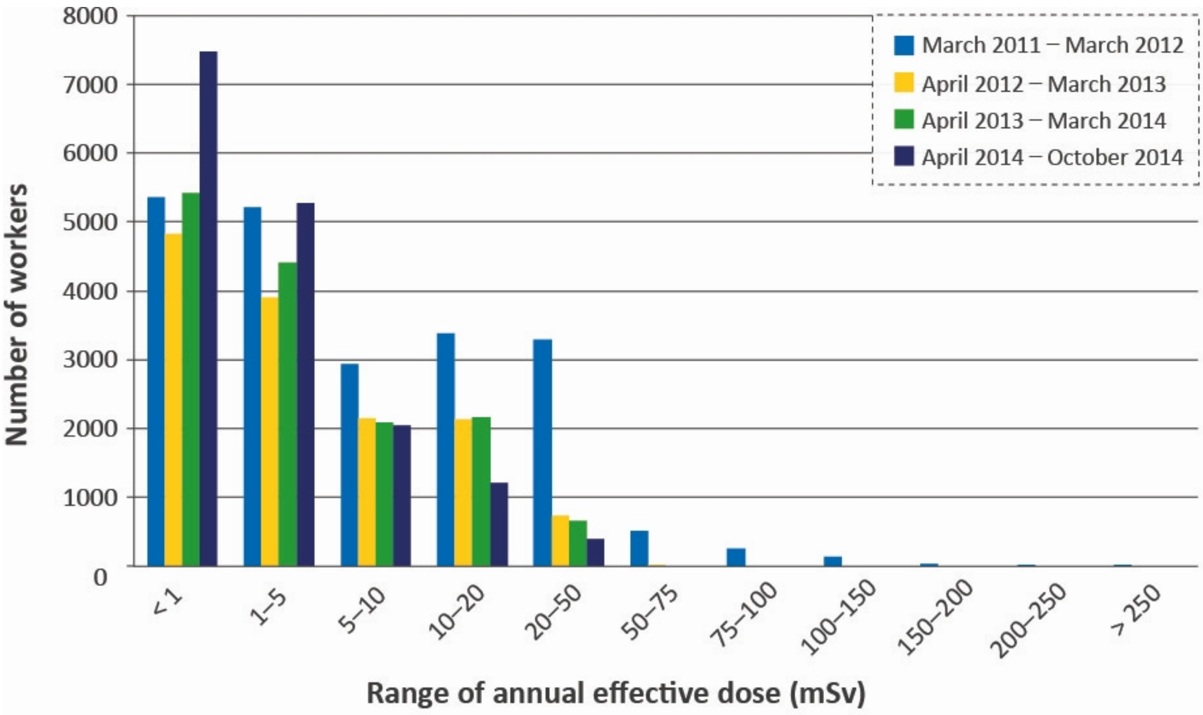


FIG. 4.11. Comparison of effective dose for emergency workers at the Fukushima Daiichi NPP between March 2011 and October 2014 (TEPCO employees and contractors). High effective doses occurred over the year following the accident. By 2012, effective doses to workers were low, and were comparable with those incurred in normal operations [215].

[96] This worker was categorized as having been subjected to the emergency dose limit of 100 mSv instead of the occupational dose limit of 50 mSv per year.

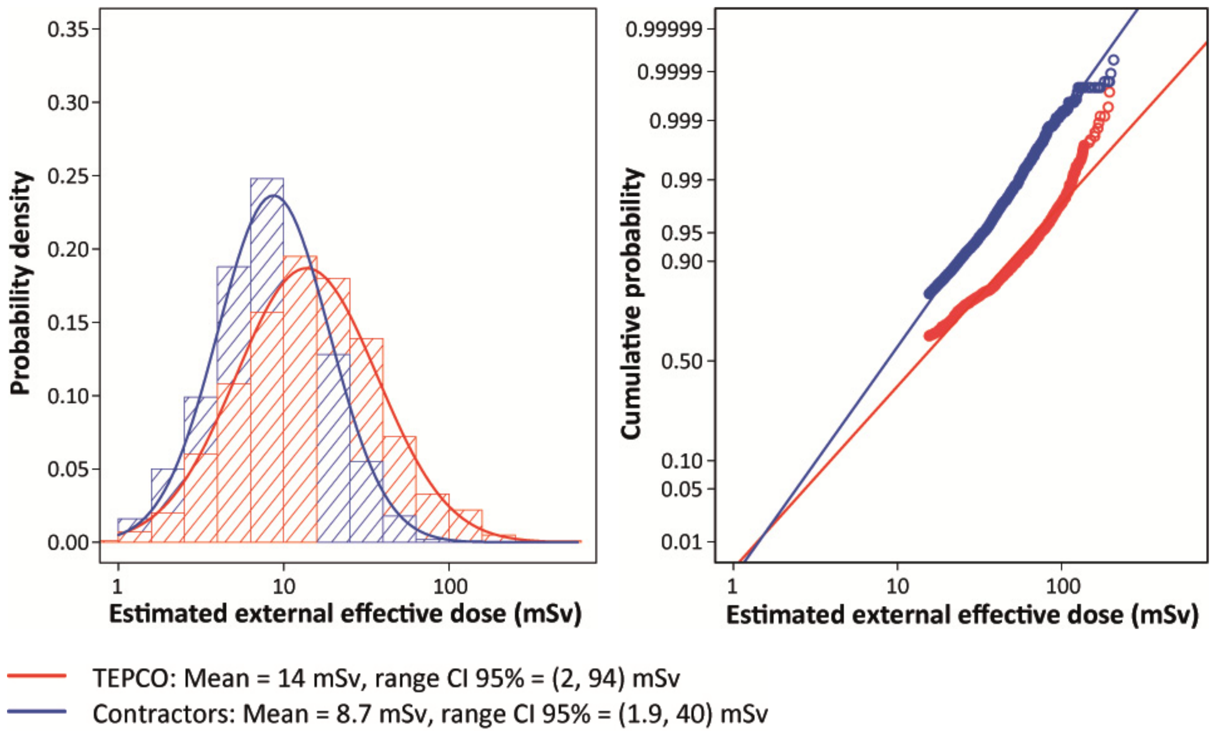


FIG. 4.12. Normalized idealized probability density distribution and cumulative probability distribution (see Box 4.6) of personal dose equivalent monitored for workers from TEPCO and contracted workers for 2011. Doses for TEPCO workers were generally higher than those of contract workers because TEPCO employees were working in higher dose areas [215].

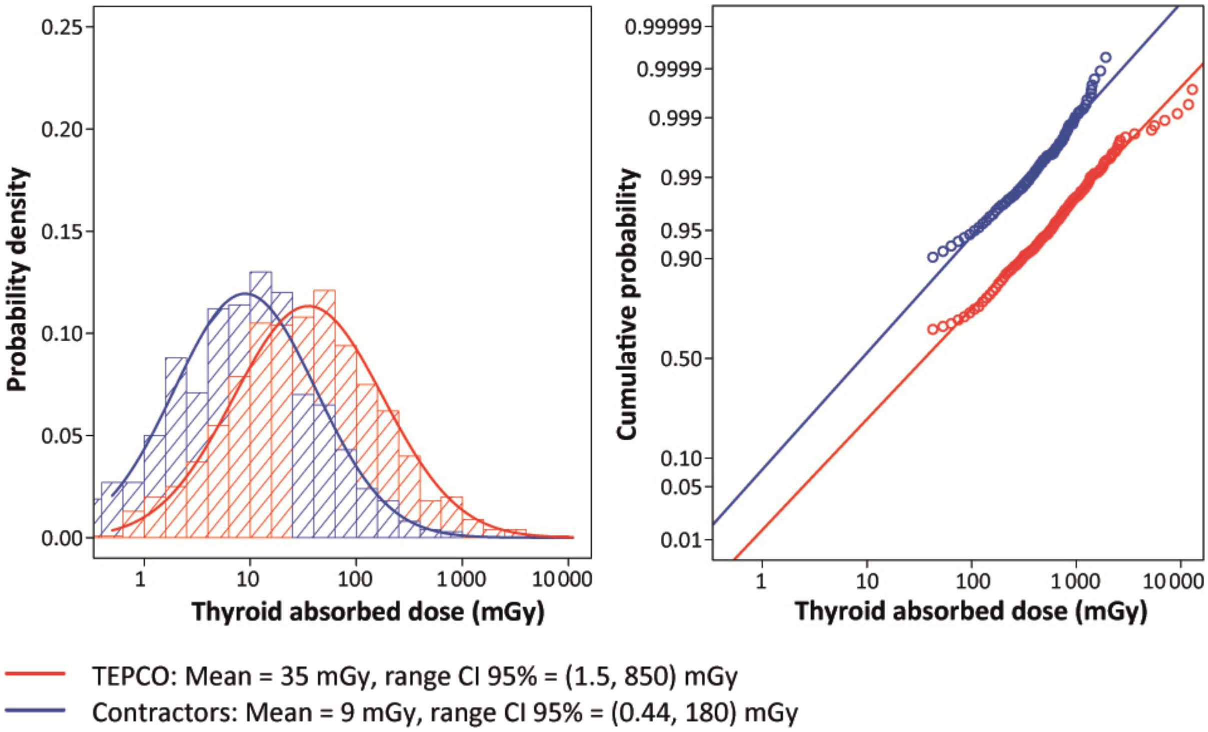
The personal dose equivalent values for both TEPCO workers and contract workers were submitted by TEPCO and were statistically analysed. The results are presented in Fig. 4.12.

In the early phase, the main contributor to effective doses, in particular to the doses incurred by the six on-site emergency workers who exceeded the temporarily revised dose criterion for emergency workers, was internal exposure from the intake of radionuclides. This was caused by challenges associated with harsh emergency working conditions, improper use of respirators and insufficient training.

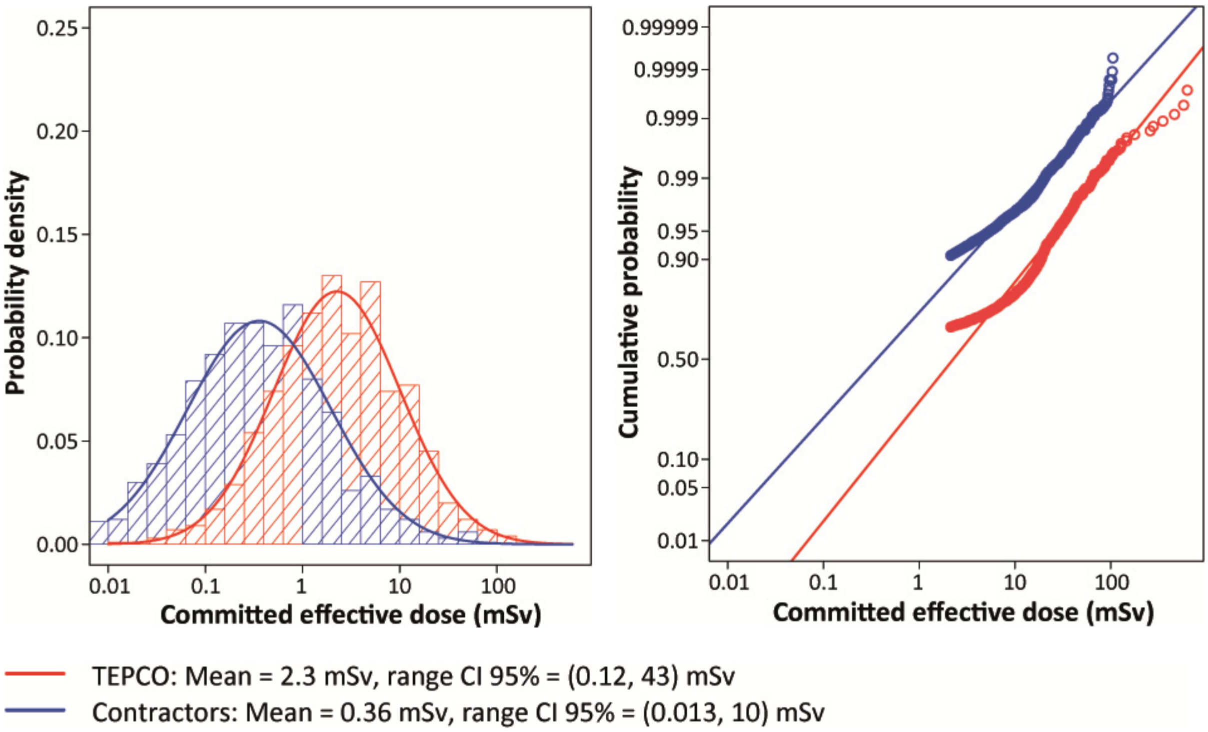
The internal doses were mostly thyroid equivalent doses from inhaled ^{131}I. Although the majority of workers at the Fukushima Daiichi NPP received thyroid equivalent doses below 100 mSv, 1757 workers received thyroid equivalent doses above this level, with 17 workers receiving thyroid equivalent doses above 2000 mSv and two receiving thyroid equivalent doses in excess of 12 000 mSv [216].

There are several uncertainties associated with the estimates of the workers' radiation doses due to internal exposure, particularly with thyroid equivalent doses. For instance, the scenario that was assumed for the incorporation of radionuclides into the body (e.g. the timing) is crucial for internal dose estimation. There was also some time lag in undertaking thyroid measurements due to the emergency operations and general post-accident conditions. The MHLW conducted a re-evaluation of the committed effective dose of emergency workers. The Ministry has promoted the standardization of methodologies of cautious assessments of internal dose in order to avoid underestimates of doses as much as reasonably achievable [217].

The statistical analysis of the distribution of the reported thyroid absorbed doses and of the estimated committed effective doses due to internal exposure is presented in Fig. 4.13.



(a)



(b)

FIG. 4.13. Normalized idealized probability density distribution and cumulative probability distribution of internal doses (see Box 4.6). (a) Thyroid absorbed dose; and (b) the consequent committed effective dose. The higher than expected distribution in the lower doses may imply that doses equivalent to the detection level were assigned to all people for whom radioactivity was undetectable [215].

The occupational exposures of workers on-site are consistent with the findings of UNSCEAR. Re-assessments of doses to TEPCO workers and contractors, which became available after the publication of the UNSCEAR report, were used in the statistical analysis of doses in this report, reducing the uncertainties. Some uncertainties remain about doses from short lived radionuclides, the influence of high background radiation in early whole body counting measurements, delays in thyroid measurements and the sufficiency of the bioassay information. Organizations in Japan are working to further reduce the uncertainties in the occupational dose assessment, specifically in the internal exposure assessments (e.g. Ref. [218]).

Firefighters, police officers and Japan Self-Defense Force personnel were also involved in a range of on-site emergency activities (see Section 3). No members of this group received effective doses in excess of 100 mSv, and the majority received effective doses of less than 10 mSv. Of over 8000 personnel who worked off the site for whom dosimetric information was available, five received effective doses in excess of 10 mSv but less than 20 mSv. The maximum effective dose recorded for police officers working off-site was around 5 mSv.

Personnel from other countries helped in the emergency. Available data show that, among those from the United States of America who assisted or performed environmental monitoring in the Fukushima area, the maximum effective dose received was 0.12 mSv for US military personnel and 0.068 mSv for US Department of Energy staff [219], all below regulatory limits. Among IAEA staff members who participated in environmental monitoring and provided advice on protection and safety, the mean effective dose was around 0.5 mSv, while one staff member received an effective dose of around 2.5 mSv from external exposure.

4.4. HEALTH EFFECTS

No early radiation induced health effects were observed among workers or members of the public that could be attributed to the accident.

The latency time for late radiation health effects can be decades, and therefore it is not possible to discount the potential occurrence of such effects among an exposed population by observations a few years after exposure. However, given the low levels of doses reported among members of the public, the conclusions of this report are in agreement with those of UNSCEAR to the United Nations General Assembly. UNSCEAR found that "no discernible increased incidence of radiation-related health effects are expected among exposed members of the public and their descendants" (which was reported within the context of the health implications related to "levels and effects of radiation exposure due to the nuclear accident after the 2011 great east-Japan earthquake and tsunami") [148]. Among the group of workers who received effective doses of 100 mSv or more, UNSCEAR concluded that "an increased risk of cancer would be expected in the future. However, any increased incidence of cancer in this group is expected to be indiscernible because of the difficulty of confirming such a small incidence against the normal statistical fluctuations in cancer incidence" [148].

The Fukushima Health Management Survey was implemented to monitor the health of the affected population of Fukushima Prefecture. This survey is aimed at the early detection and treatment of diseases, as well as prevention of lifestyle related diseases. At the time of writing, an intensive screening of children's thyroid glands is taking place as part of the survey. Highly sensitive equipment is being used, which has detected asymptomatic thyroid abnormalities among a significant number of surveyed children (which would not have been detectable by clinical means). The abnormalities identified in the survey are unlikely to be associated with radiation exposure from the accident and most probably denote the natural occurrence of thyroid abnormalities in children of this age. The incidence of thyroid cancer in children is the most likely health effect

after an accident involving significant releases of radioiodine. Because the reported thyroid doses attributable to the accident were generally low, an increase in childhood thyroid cancer attributable to the accident is unlikely. However, uncertainties remained concerning the thyroid equivalent doses incurred by children immediately after the accident.

Prenatal radiation effects have not been observed and are not expected to occur, given that the reported doses are well below the threshold at which these effects may take place. Unwanted terminations of pregnancy attributable to the radiological situation have not been reported. Concerning the possibility of parents' exposures resulting in hereditary effects in their descendants, UNSCEAR concluded that, in general, "although demonstrated in animal studies, an increase in the incidence of hereditary effects in human populations cannot at present be attributed to radiation exposure" [167].

Some psychological conditions were reported among the population affected by the nuclear accident. Since a number of these people had suffered the combined impacts of a major earthquake and a devastating tsunami as well as the accident, it is difficult to assess to what extent these effects could be attributed to the nuclear accident alone. The Fukushima Health Management Survey's Mental Health and Lifestyle Survey shows associated psychological problems in some vulnerable groups of the affected population, such as increases in anxiety and post-traumatic stress disorders. UNSCEAR estimated that "The most important health effect [from the accident] is on mental and social well-being, related to the enormous impact of the earthquake, tsunami and nuclear accident, and the fear and stigma related to the perceived risk of exposure to ionizing radiation" [148].

A comprehensive health check of the affected population is being carried out under the Fukushima Health Management Survey, described in Box 4.2. The programme aims at the early detection and treatment of diseases, as well as the prevention of lifestyle related diseases. Additional tests, such as differential leukocyte counts, are being performed in addition to routine general medical check-ups at the workplace or by the local government [220].

4.4.1 Early radiation induced health effects

Radiation exposure can induce health effects caused by the killing of cells. The severity of these effects increases with dose, and they can range from skin injuries to the collapse of vital tissues. Most of these effects occur early after a dose is incurred above the threshold levels that are known for each potential effect. The available information indicates that no individual received a dose at or above these threshold levels to cause acute radiation effects as a result of the accident. Two workers were exposed on their legs from contaminated water from the turbine hall. The skin equivalent doses of these workers were reported to be lower than the estimated threshold for deterministic effects[97] [81] and the applicable international limits[98] [222].

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[97] ICRP estimates for the exposure of the skin are that an early response, such as early transient erythema, is seen a few hours after doses of >2000 mGy, when the exposed area is relatively large. The ICRP also estimates that the approximate threshold doses are as follows: early transient erythema 2000 mGy, main erythema reaction 6000 mGy, temporary epilation 3000 mGy, permanent epilation 7000 mGy, dry desquamation 14 000 mGy, moist desquamation 18 000 mGy, secondary ulceration 24 000 mGy, late erythema 15 000 mGy, ischaemic dermal necrosis 18 000 mGy, dermal atrophy (first phase) 10 000 mGy, telangiectasia 10 000 mGy and dermal necrosis (late phase) >15 000 mGy [221].

[98] The recommended occupational dose limit for skin in planned exposure situations is an equivalent dose of 500 mSv/year, averaged over 1 cm^2 area of skin regardless of the area exposed (see table 6 in Ref. [129] and schedule III in Ref. [198]). The generic criterion established for acute doses to the skin, for which protective actions and other response actions are expected to be undertaken under any circumstances to avoid or to minimize severe deterministic effects, is 10 000 mGy incurred in a 100 cm^2 dermis (skin structures at a depth of 40 mg/cm^2 (or 0.4 mm) below the surface) (see table IV.1 in Ref. [198]).

UNSCEAR already observed that: “No radiation related deaths or acute diseases have been observed among the workers and general public exposed to radiation from the accident” [223].

4.4.2 Potential late radiation induced health effects

Under the severe circumstances and conditions of the accident, of the approximately 23 000 workers involved in emergency operations, the number exceeding a dose of 100 mSv was 174. UNSCEAR concluded that among this group “an increased risk of cancer would be expected in the future. However, any increased incidence of cancer in this group is expected to be indiscernible because of the difficulty of confirming such a small incidence against the normal statistical fluctuations in cancer incidence” [223].

With reference to potential late effects among members of the public, international estimates were published before this report (see Box 4.1). WHO issued a hypothetical estimate[99] of additional lifetime risks over baseline rates for the development of leukaemia, breast cancer, thyroid cancer and all solid cancers for the population in the locations with the highest dose rates, which was based on WHO preliminary dose estimates[100] [146, 147].

UNSCEAR, following its updated dose estimate, reported that:

> “The doses to the general public, both those incurred during the first year and estimated for their lifetimes, are generally low or very low. No discernible increased incidence of radiation-related health effects are expected among exposed members of the public or their descendants” [223].

Before reporting on the accident, UNSCEAR had informed the United Nations General Assembly that “increases in the incidence of health effects in populations cannot be attributed reliably to chronic exposure to radiation at levels that are typical of the global average background levels of radiation” [167]. The information available indicates that members of the public incurred annual doses that were not higher than annual doses due to typical background levels of radiation. This indicates that no discernible increased incidence of radiation related health effects is expected among exposed members of the public or their descendants, in agreement with UNSCEAR estimates.

This estimate is also generally applicable to the special case of adult thyroid cancer. In adult life, this risk is very much lower than that from radiation exposure in childhood (see the discussion of thyroid effects in children below). Given the reported radiation equivalent doses to the thyroid, it is unlikely that there would be a discernible increase in thyroid cancers among the adult population.

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[99] Given the limited information available at the time, the assessment contained a number of conservative assumptions. WHO indicated that “all efforts were made to avoid any underestimation of doses” and that “some possible dose overestimation may have occurred” [146].

[100] WHO’s health risk assessment estimated that “in the two most affected locations of Fukushima Prefecture, the preliminary estimated radiation effective doses for the first year ranged from 12 to 25 mSv” and that, on the basis of these estimates, “in the highest dose location, the estimated additional lifetime risks for the development of leukaemia, breast cancer, thyroid cancer and all solid cancers over baseline rates are likely to represent an upper bound of the risk as methodological options were consciously chosen to avoid underestimation of risks. For leukaemia, the lifetime risks are predicted to increase by up to around 7% over baseline cancer rates in males exposed as infants; for breast cancer, the estimated lifetime risks increase by up to around 6% over baseline rates in females exposed as infants; for all solid cancers, the estimated lifetime risks increase by up to around 4% over baseline rates in females exposed as infants; and for thyroid cancer, the estimated lifetime risk increases by up to around 70% over baseline rates in females exposed as infants. These percentages represent estimated relative increases over the baseline rates and are not estimated absolute risks for developing such cancers” [147].

For the few workers who received high thyroid equivalent doses (see Section 4.3.2), an increased risk of developing thyroid disorders could be inferred. These thyroid equivalent dose levels can reduce the function of the gland to such an extent that hypothyroidism ensues. Hyperthyroidism is not expected because the reported thyroid equivalent doses are below the level of around 15 000 mSv, above which such effects could occur. Effects for low and medium thyroid equivalent doses, typical of the range of doses received by the emergency workers, are difficult to quantify, and the potential for and magnitude of effects remains unclear.

4.4.3 Radiation effects in children

The potential for radiation effects in children is an issue of special concern. International recommendations and standards for radiation protection take account of children in an exposed population. For radiation protection purposes, they postulate a potential nominal radiation risk for an entire population, i.e. a population including children[101], that is about 30% higher than the postulated risk for an adult population (such nominal risks have been estimated on the basis of epidemiological studies of populations exposed to high radiation doses) [129, 224].

Thyroid effects in children

For thyroid cancer, children are more radiosensitive than adults. For a given intake of radioiodines, the dose to the thyroid for infants is eight or nine times as large as that for adults. A substantial environmental presence of ^{131}I can result in thyroid cancer in children. The normal incidence of some types of thyroid cancer in children is low and the sensitivity of children's thyroid glands to radiation is high. Owing to this higher sensitivity, in the aftermath of the accident it was important to undertake follow-up screening in order to detect early any potential increase in the incidence of this type of cancer [225].

The results of three years of thyroid ultrasound examinations performed under the Fukushima Health Management Survey were reported [226]. The screening covered roughly 370 000 children aged 0–18 years at the time of the accident. This initial screening was followed by complete thyroid examinations from 2014 onwards, and the residents will be monitored regularly in subsequent years.

The examinations use highly sensitive ultrasound sonography equipment for screening the thyroid gland. The screening has detected asymptomatic[102] thyroid abnormalities — nodules, cysts and cancers — that would have gone undetected if asymptomatic children had been screened using standard equipment. Similar results were obtained when the same screening was carried out on children living far away from the areas affected by the accident [227]. The latency time for radiation induced thyroid cancer is longer than the four years that have elapsed since the accident, at the time of writing. In many cases, thyroid cancers were found in children in their late teenage years, but no cases were found in the most vulnerable group of children, who were aged under five years on 11 March 2011. The proportion of suspicious or malignant cases was almost the same among regions in Fukushima Prefecture in the initial screening conducted in 2011–2013 [228]. These factors suggest that the thyroid abnormalities detected in the survey are unlikely to be associated with radiation exposure due to the accident.

On the basis of the data made available on indirect measurements of external dose equivalent due to activity in the thyroid (see Fig. 4.10), thyroid equivalent doses in children appear to have been low.

[101] The term 'children' includes those exposed as infants, children and adolescents.

[102] Asymptomatic effects are those that produce no symptoms, i.e. nothing that indicates a condition of disease, in particular nothing apparent to the children, to their parents or even to doctors.

For the levels of doses reported, increases in thyroid cancer in children would not be attributable to radiation exposure.

4.4.4 Prenatal radiation induced health effects

A ‘prenatal (or ‘antenatal’) effect of exposure’ is the term used to refer to effects of radiation on the embryo and foetus. At absorbed doses under 100 mGy, lethal effects of irradiation in the pre-implantation period of embryonic development are considered to be very infrequent, and there is an absorbed dose threshold of around 100 mGy for the induction of other effects [229–231]. Absorbed doses to the embryo and foetus that could be attributable to the accident were much lower than the threshold absorbed dose for the occurrence of these effects.

The pregnancy survey carried out as part of the Fukushima Health Management Survey (see Box 4.2) helped the provision of appropriate medical care and support to mothers who were given a Maternal and Child Health Handbook between 1 August 2010 and 31 July 2011, and to their children. This survey is being updated every year to take account of new data, particularly on pregnancy and births [162]. The aim was to collect data that might improve obstetrical and prenatal care and to support women who were pregnant or gave birth in Fukushima Prefecture following the accident. On the basis of the survey results, there were no significant adverse outcomes, and the incidences of stillbirth, pre-term birth, low birth weight and congenital abnormalities were found to be similar to those elsewhere in Japan [232].

UNSCEAR reported to the United Nations General Assembly that “although demonstrated in animal studies, an increase in the incidence of hereditary effects in human populations cannot at present be attributed to radiation exposure” [167]. Therefore, the findings in this report indicate that no heritable effects will be attributable to the accident.

Following accidents involving significant potential for radiation exposure, some pregnant women seek medical advice on whether or not their pregnancy should be terminated. In the case of the Fukushima Daiichi accident, a study by the Obstetrics and Gynaecology Department of the Fukushima Medical University reported that no such elective terminations had been carried out in the aftermath of the accident [232, 233].

4.4.5 Psychological consequences

Although not directly attributable to radiation exposure, psychological consequences were considered in this report. UNSCEAR reported that:

> “The most important health effect is on mental and social well-being, related to the enormous impact of the earthquake, tsunami and nuclear accident, and the fear and stigma related to the perceived risk of exposure to ionizing radiation. Effects such as depression and post-traumatic stress symptoms have already been reported.” [148]

A number of studies on psychological conditions following the Fukushima Daiichi accident have been performed. These studies focused largely on pregnant women and mothers of infants, rescue and cleanup workers, and evacuees. Some psychological consequences have been detected in the affected population [234–244][103]. According to these studies, communication and dissemination of accurate

[103] Psychological consequences have been detected in other traumatic situations and may include depression, post-traumatic stress responses, chronic anxiety, sleep disturbance, severe headaches and increased smoking and use of alcohol, as well as dysfunctional behaviour such as intense anger, despair, extreme anxiety about health, and feelings of stigmatization and discrimination. As demonstrated after previous accidents, such as the Chernobyl accident, the majority of people affected are generally resilient to psychological conditions, but exceptions have been reported in a number of studies [169, 245–247].

information to the public at an early stage and during the development of the accident contributed to the alleviation of undesired psychological reactions [150].

The largest study is the Mental Health and Lifestyle Survey, conducted as part of the Fukushima Health Management Survey [248], which aims at providing adequate care mainly for evacuees who are at a higher risk of developing mental health problems such as post-traumatic stress disorder, anxiety and stress. The questionnaires contained standard measures of symptoms of post-traumatic stress disorder and psychological distress (anxiety) as well as questions about concerns regarding radiation exposure and adversity resulting from the earthquake and tsunami (e.g. loss of family or relatives, damage to houses, loss of employment, decrease in income, movement within or outside Fukushima Prefecture).

The results of the Mental Health and Lifestyle Survey were published [236]. They confirmed that the affected population experienced considerable distress and symptoms of post-traumatic stress disorder. The survey indicated that "sociodemographic data showed that many evacuee households were separated after the disaster and had to move several times", suggesting this was a cause of psychological conditions.

Two other methods were used to assess the mental health status of adult evacuees [249, 250] and an additional survey was performed to assess alcoholism [251]. These surveys indicated that mental health symptoms were substantially worse than would be expected from surveys of the general population [237]. Children's mental health status was assessed using another questionnaire approach [252, 253], which suggested some psychological difficulties among the surveyed children, but with relative improvements year by year.

Studies were also performed on the affected workers. A study comparing workers at the Fukushima Daiichi and Fukushima Daini NPPs in April–June 2011 found significantly more symptoms of general psychological distress and post-traumatic stress responses among Fukushima Daiichi workers (see Fig. 4.14). In both groups of workers, there were also statistically significant associations between experiencing discrimination and slurs and symptoms of both these conditions.

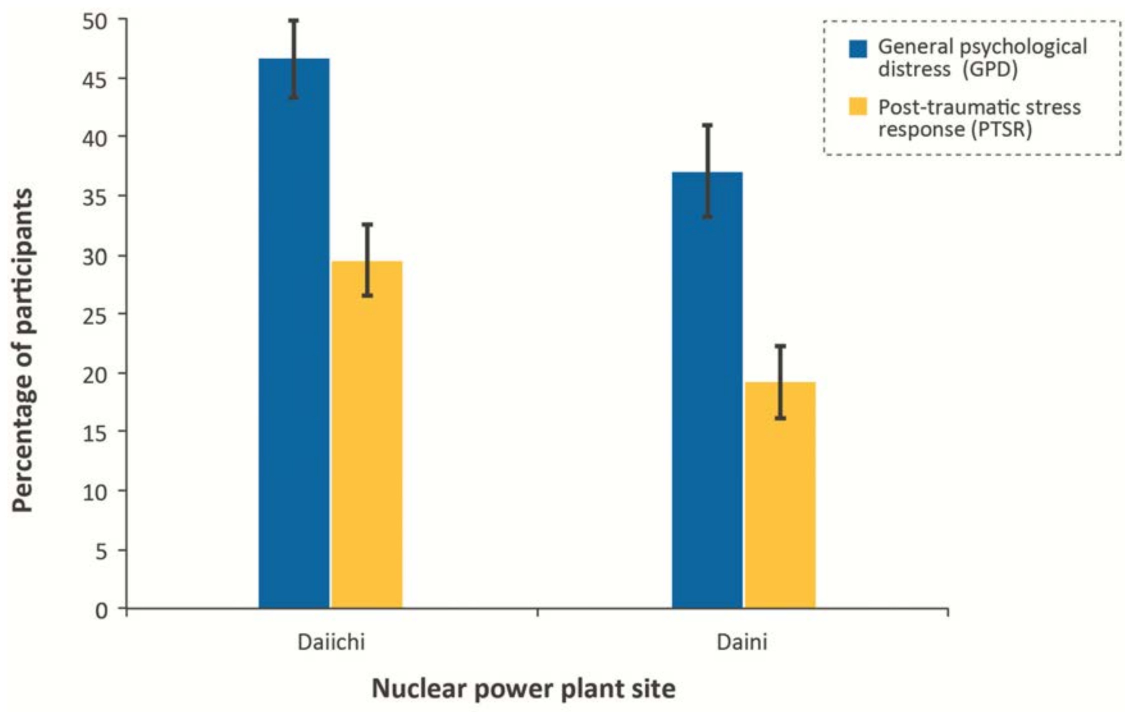

FIG. 4.14. Percentage of workers at the Fukushima Daiichi and Fukushima Daini NPPs reporting psychological distress, April 2011 [242].

4.5. RADIOLOGICAL CONSEQUENCES FOR NON-HUMAN BIOTA

No observations of direct radiation induced effects in plants and animals have been reported, although limited observational studies were conducted in the period immediately after the accident. There are limitations in the available methodologies for assessing radiological consequences, but, based on previous experience and the levels of radionuclides present in the environment, it is unlikely that there would be any major radiological consequences for biota populations or ecosystems as a consequence of the accident.

Protection of the environment[104] includes "the protection and conservation of: non-human species, both animal and plant, and their biodiversity; environmental goods and services. The term also includes the production of food and feed; resources used in agriculture, forestry, fisheries and tourism; amenities used in spiritual, cultural and recreational activities; media, for example soil, water and air; and natural processes, such as carbon, nitrogen and water cycles" [198]. The earthquake and tsunami caused significant environmental stress to the terrestrial and marine environments along the north-eastern coast of Honshu [254, 255].[105]

The immediate priority following the accident was the protection of people rather than species in the environment, for which exposures are not easy to control. Although residents within a 20 km radius of the plant were evacuated in order to reduce their radiation exposures, the exposure of non-human organisms inhabiting these areas was unavoidable. The approaches used in this report to assess the potential radiological impact of the accident on non-human organisms were those recommended by the ICRP [224, 257]. The estimated exposures were then compared with information on the impact of such exposures on different types of plants and animals as published in the literature (see Refs [258, 259]).

The overall uncertainties associated with the types of models applied in this assessment are large, particularly where assumptions about environmental transfers are involved [260]. These assessment methodologies tend to be based on simple assumptions, and uncertainties are usually taken into account by the use of conservative assumptions. The benchmarks used to relate calculated doses to radiation effects are primarily related to chronic rather than acute exposures and to a limited range of individual organisms rather than populations or ecosystems. The current methodologies do not take account of interactions between components of ecosystems or the combined impact of radiation and other environmental stressors. There is a need for improvements in both the assessment methodologies and in the understanding of radiation induced effects to ecosystems.

The estimated absorbed doses were highest for plants during the first weeks after the accident, but remained below levels at which acute effects would be anticipated. The relevant reference levels were exceeded for some terrestrial reference organisms (such as pine, grass, deer and rats) in the early phase following the accident. However, no overall impact on the populations of these organisms or the ecosystems has been observed.

Earlier publications by UNSCEAR [261, 262] reported that minor damage could occur in conifers at doses below 1.2 Gy, while more serious damage, leading to death, could occur at doses in the range of 10–20 Gy. From the assessed doses it is possible to infer that any direct lethal effects are unlikely on wild grass, as it is more radioresistant. For the terrestrial animals, the estimated dose rates in the early phase indicated that there is a low probability of reproductive disturbances.

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[104] In this report, the term 'environment' refers to the "conditions under which people, animals and plants live or develop and which sustain all life and development; especially such conditions as affected by human activities" [198].

[105] Other reports of the effect of the tsunami on the ecosystems can be found in Ref. [256].

Although dose rates exceeded some reference values in the early phases of the accident, no impact on animal and plant populations and ecosystems is expected. Long term effects are also not expected, as the estimated short term doses were generally well below levels at which highly detrimental acute effects might be expected and dose rates declined relatively rapidly after the accident.

4.6. OBSERVATIONS AND LESSONS

A number of observations and lessons have been compiled as a result of the assessment of the radiological consequences of the accident.

— **In case of an accidental release of radioactive substances to the environment, the prompt quantification and characterization of the amount and composition of the release is needed. For significant releases, a comprehensive and coordinated programme of long term environmental monitoring is necessary to determine the nature and extent of the radiological impact on the environment at the local, regional and global levels.**
  The quantification and characterization of the source term of the accident at the Fukushima Daiichi NPP proved to be difficult. Prompt monitoring of the environment provides confirmation of the levels of radionuclides and establishes the initial basis for protecting people. The results can be used to inform the public and to develop strategies for response and recovery activities. It is also important to continue environmental monitoring to verify that there are no further significant releases of radionuclides and to provide information to decision makers and other stakeholders on the possible redistribution of radionuclides in the environment over time.

— **Relevant international bodies need to develop explanations of the principles and criteria for radiation protection that are understandable for non-specialists in order to make their application clearer for decision makers and the public. As some protracted protection measures were disruptive for the affected people, a better communication strategy is needed to convey the justification for such measures and actions to all stakeholders, including the public.**
  There is a recognized need for simple explanations of a number of radiation protection issues, including:
  - Differences between the concepts of dose limits and reference levels and the associated rationale;
  - Criteria for the justification of protective measures and actions aimed at averting radiation doses in the long term, in particular when they involve significant disruptions to normal life;
  - Specific situations relating to the radiation protection of workers in an emergency.

  The principles of radiation protection are based not solely on science, but also on value judgements based on ethical principles. In some circumstances, protective measures and actions involve protracted social disruption. Under these circumstances, the potential benefit from avoiding radiation doses must outweigh the individual and social detriment caused by the protective measures and actions themselves. It is important to explain to stakeholders the justification for long-standing radiation protection measures and actions.

— **Conservative decisions related to specific activity and activity concentrations in consumer products and deposition activity led to extended restrictions and associated difficulties. In a prolonged exposure situation, consistency among international standards, and between international and national standards, is beneficial, particularly those associated with drinking water, food, non-edible consumer products and deposition activity on land.**
  The Japanese authorities established measures for controlling the presence of radioactive substances in consumer products, which were generally more stringent than the available international guidance. The current international system for controlling radioactivity in consumer products is governed by distinct guidance, for example the Codex Alimentarius for food (including bottled water) in international trade, IAEA safety standards for food and drinking water for use in an emergency, WHO guidelines for drinking water in existing exposure situations and

IAEA safety standards for non-edible products for exemption purposes. There is a need for consistency in the international standards for acceptable levels of radioactivity in products for public consumption in order to facilitate their application by regulatory bodies and their understanding by the public. National standards need to be in line with international standards, where this is feasible. Moreover, there is a need for criteria for dealing with the protracted presence of radionuclides on land.

— **Personal radiation monitoring of representative groups of members of the public provides invaluable information for reliable estimates of radiation doses and needs to be used together with environmental measurements and appropriate dose estimation models for assessing public dose.**

The early estimation of doses was based on environmental measures and modelling, resulting in some conservative assumptions on doses incurred and projected.

Personal monitoring of ^{131}I in the thyroids of children needs to be undertaken as soon as possible following radioiodine releases to the environment, owing to the short half-life of this radionuclide. Personal monitoring of external radiation and the internal presence of the longer lived radionuclides (e.g. ^{137}Cs) needs to be undertaken as soon as feasible and to continue over time, as appropriate.

In the absence of personal radiation measurements, modelling of environmental and ambient data may be needed to estimate the radiation doses incurred by individuals. In these cases, the uncertainties associated with the assumptions used in the models need to be clearly explained, particularly if the results are being used to inform decision making on protective measures and actions or to estimate the potential for radiation induced health effects.

— **While dairy products were not the main pathway for the ingestion of radioiodine in Japan, it is clear that the most important method of limiting thyroid doses, especially to children, is to restrict the consumption of fresh milk from grazing cows.**

The estimates of thyroid doses to children following the accident were low. This was the result of a combination of factors, including the time of year (before the growing season), agricultural practices in Japan, low consumption of cow's milk by infants and the controls on milk consumption that were immediately introduced. These factors contributed to the low level of intake of ^{131}I.

— **A robust system is necessary for monitoring and recording occupational radiation doses, via all relevant pathways, particularly those due to internal exposure that may be incurred by workers during severe accident management activities. It is essential that suitable and sufficient personal protective equipment be available for limiting the exposure of workers during emergency response activities and that workers be sufficiently trained in its use.**

Early and continued direct measurements of the radiation exposure and the levels of radionuclides incorporated by emergency workers are the most valuable approach to obtaining information for estimating radiation risks and potential health effects and to optimizing protection. There is a need to monitor and register occupational radiation doses through a robust system of personal dosimeters and measurements. Monitoring of ^{131}I in the thyroid needs to be undertaken as soon as possible.

Immediately following the Fukushima Daiichi accident, the provision of personal protective equipment for restricting the exposure of workers and monitoring was difficult.

— **The risks of radiation exposure and the attribution of health effects to radiation need to be clearly presented to stakeholders, making it unambiguous that any increases in the occurrence of health effects in populations are not attributable to exposure to radiation if levels of exposure are similar to the global average background levels of radiation.**

In the case of the Fukushima Daiichi accident, doses to members of the public were low and comparable with typical global average background doses. There is a need to clearly inform the public, particularly the people affected, that no discernible increased incidence of radiation related health effects is expected among exposed members of the public and their descendants as a result of the accident.

An understanding of radiation and its possible health effects is important for all those involved in an emergency, in particular for physicians, nurses, radiation technologists and medical first responders. This needs to be ensured through appropriate education and training of medical professionals in the topics of radioactivity, radiation and health effects associated with radiation exposure.

— **After a nuclear accident, health surveys are very important and useful, but should not be interpreted as epidemiological studies. The results of such health surveys are intended to provide information to support medical assistance to the affected population.**

The Fukushima Health Management Survey provides valuable health information for the local community, helping to ensure that any health effects are detected quickly, and that appropriate actions are taken to protect the health of the population. The overall results of health checks may provide important information, but they should not be misinterpreted as the results of an epidemiological assessment.

— **There is a need for radiological protection guidance to address the psychological consequences to members of the affected populations in the aftermath of radiological accidents. A Task Group of the ICRP has recommended that "strategies for mitigating the serious psychological consequences arising from radiological accidents be sought" [149].**

Psychological conditions have been reported as a consequence of the accident. This has been a repeated issue in the aftermath of accidents involving radiation exposure. In spite of their importance, these consequences have not been recognized in international recommendations and standards on radiological protection.

— **Factual information on radiation effects needs to be communicated in an understandable and timely manner to individuals in affected areas in order to enhance their understanding of protection strategies, to alleviate their concerns and support their own protection initiatives.**

Arrangements at the national and local level need to be put in place to share information in an understandable manner with the public who may be affected by accidents with radiological consequences. The arrangements need to allow for person to person dialogue so that individuals can seek clarifications and express their concerns. These arrangements will require the concerted efforts of the relevant authorities, experts and professionals in supporting and advising the affected individuals and communities. Sharing information is important when conveying decisions to protect these individuals, including the support of their own initiatives.

— **During any emergency phase, the focus has to be on protecting people. Doses to the biota cannot be controlled and could be potentially significant on an individual basis. Knowledge of the impacts of radiation exposure on non-human biota needs to be strengthened by improving the assessment methodology and understanding of radiation induced effects on biota populations and ecosystems. Following a large release of radionuclides to the environment, an integrated perspective needs to be adopted to ensure sustainability of agriculture, forestry, fishery and tourism, and of the use of natural resources.**

It may be difficult to substantially reduce doses to non-human biota because of the impracticability of introducing countermeasures. Impact assessments for plants and animals in the aftermath of accidents such as that at the Fukushima Daiichi NPP require consideration of numerous potential stressors — radiation exposure being one of many. Consideration also needs to be given to the potential for the buildup and accumulation of long lived radionuclides in the environment and how this might affect plants and animals over multiple generations.

5. POST-ACCIDENT RECOVERY

Immediately following the accident at the Fukushima Daiichi NPP, priority was given to stabilizing conditions at the plant and protecting the public through actions that included sheltering and evacuation of residents in the affected areas and restrictions on food[106] and drinking water. As work progressed and conditions at the site were stabilized, greater emphasis was placed on recovery from the accident, including the revitalization of the community and infrastructure.

This section considers progress in post-accident recovery up until March 2015 as well as plans for the future. It considers, primarily, the existing exposure situation that followed the emergency phase.

5.1. OFF-SITE REMEDIATION OF AREAS AFFECTED BY THE ACCIDENT

The long term goal of post-accident recovery[107] is to re-establish an acceptable basis for a fully functioning society in the affected areas. Consideration needs to be given to remediation[108] of the areas affected by the accident in order to reduce radiation doses, consistent with adopted reference levels. In preparing for the return of evacuees, factors such as the restoration of infrastructure and the viability and sustainable economic activity of the community need to be considered.

Prior to the Fukushima Daiichi accident, policies and strategies for post-accident remediation were not in place in Japan, and it became necessary to develop them in the period after the accident. The remediation policy was enacted by the Government of Japan in August 2011.[109] It assigned responsibilities to the national and local governments, the operator and the public, and created the necessary institutional arrangements for the implementation of a coordinated work programme.

A remediation strategy was developed and implementation began. The strategy specifies that priority areas for remediation are residential areas, including buildings and gardens, farmland, roads and infrastructure, with emphasis on the reduction of external exposures.

External dose from radionuclides deposited on the ground and other surfaces is the main pathway of exposure. The remediation strategy is therefore focused on decontamination activities to reduce the levels of radiocaesium present in priority areas, thereby reducing the potential for such exposures. Internal doses continue to be controlled by restrictions on food, as well as through remediation activities on agricultural land.

Following the accident, the authorities in Japan adopted a 'reference level' as a target level of dose for the overall remediation strategy. This level was consistent with the lower end of the range specified in international guidance. The application of a low reference level has the effect of increasing the quantity of contaminated materials generated in remediation activities, and thereby

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[106] Including restrictions on the distribution and sale of food, the use of agricultural land and the collection of wild food products (see Section 3.3).

[107] Post-accident recovery includes: remediation of areas affected by the accident; the stabilization of damaged on-site facilities and preparations for decommissioning; the management of contaminated material and radioactive waste arising from these activities; and community revitalization and stakeholder engagement.

[108] Remediation is defined as any measures that may be carried out to reduce the radiation exposure from existing contamination of land areas through actions applied to the contamination itself (the source) or to the exposure pathways to humans.

[109] Act on Special Measures Concerning the Handling of Environmental Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District — Off the Pacific Ocean Earthquake that Occurred on March 11, 2011, Act No. 110, 2011.

increasing the costs and the demands on limited resources. The experience obtained in Japan could be used in developing practical guidance on the application of international safety standards in post-accident recovery situations.

Two categories of contaminated areas were defined on the basis of additional annual doses estimated in the autumn of 2011. The national Government was assigned responsibility for formulating and implementing remediation plans in the first area (the 'Special Decontamination Area') — within a radius of 20 km of the Fukushima Daiichi site and in areas where additional annual doses arising from contamination on the ground were projected to exceed 20 mSv in the first year after the accident. The municipalities were given responsibility for implementing remediation activities in the other area (the 'Intensive Contamination Survey Area'), where the additional annual doses were projected to exceed 1 mSv but to remain below 20 mSv. Specific dose reduction goals were set, including a long term goal of achieving an additional annual dose of 1 mSv or less.

5.1.1. Establishment of a legal and regulatory framework for remediation

Following the accident, a policy on recovery and remediation was established by the Government of Japan through the enactment of the 'Act on Special Measures Concerning the Handling of Environment Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District — Off the Pacific Ocean Earthquake that Occurred on March 11, 2011', in August 2011 [124]. The Act includes provisions for prioritization of sites to be remediated, allocation of funds to carry out the remediation work and involvement of stakeholders in the overall process.

The first steps in developing a remediation programme are the definition of appropriate reference levels and the establishment of a remediation strategy to achieve the required reduction in the radiation exposure of members of the public. International guidance recommends that a reference level be selected from the range of additional dose of 1–20 mSv/year, depending on the prevailing circumstances (Box 5.1) [129, 198, 263].[110]

It is important in setting reference levels within this range that they are not too high, which could jeopardize the required safety objective, or too low, which could result in a less than optimal use of limited resources. In the initial stages of remediation in Japan in 2011, the Government of Japan set reference levels that were intentionally low [264, 265], and a long term goal for residents, following remediation, of an additional dose of no more than 1 mSv/year was adopted [266]. This is the lowest value in the range given in international guidance (Box 5.1).

The high level of conservatism in the approach used to estimate doses to people was illustrated by an assessment by UNSCEAR [148]. The estimated doses are based on the activity per unit area of ^{134}Cs and ^{137}Cs, taking into account the decline of activity due to decay, the loss of activity due to weathering from surfaces and the shielding factor typical for wooden houses. Calculations undertaken for the purpose of this report, using the same methodology used by UNSCEAR [148, 267], indicated that the average additional radiation doses in 2012 in large parts of the Intensive Contamination Survey Area (see Section 5.1.2) would have been well below 1 mSv/year.

[110] A pre-publication version of the interim edition of the International Basic Safety Standards was available at the time of the accident [263]. IAEA Safety Standards Series No. GSR Part 3 [198] was subsequently published in 2014.

Box 5.1. Reference level for remediation

The ‘reference level’ is the target dose for the overall remediation strategy, but it is not a dose limit. International guidance [129, 263] recommends reference levels in the range of 1–20 mSv/year for additional exposure of a member of the public in ‘existing exposure situations’, depending on the prevailing circumstances.

Reference levels are established by the Government, the regulatory body or another relevant authority, according to the arrangements in the national regulatory framework. Reference levels in post-accident situations are used to identify optimal strategies for remediation. These strategies will ensure that remediation is performed through the efficient use of available human, technical and financial resources to achieve the best outcomes in the protection of the affected communities.

Specific actions applied to reduce environmental contamination and radiation doses to people are generally guided by derived ‘remediation action levels’. Usually, these are specified in terms of easily measurable quantities, such as ambient gamma dose rates (μSv/h) or deposited activity per unit area (Bq/m^2), and derived from the reference levels by using models and assumptions about people’s living habits and about the behaviour of radionuclides in the environment.

5.1.2. Remediation strategy adopted

The remediation strategy was influenced by the fact that internal doses following the accident were largely avoided by implementing restrictions on food and drinking water. As a consequence, the remediation actions described here were primarily concerned with decontamination efforts to reduce the levels of external doses.

The Government of Japan’s remediation strategy set an approach to the rapid reduction of radiation dose, prioritizing remediation in residential areas, on farmland and in forest areas adjacent to residential or agricultural areas [124, 266]. To facilitate this, in August 2011, it classified the land to be remediated as follows:

- **Special Decontamination Area** (Fig. 5.1, right). This area overlaps the former ‘Restricted Area’, i.e. the evacuation zone within a 20 km radius of the Fukushima Daiichi NPP, and the former ‘Deliberate Evacuation Area’, which were situated beyond the 20 km radius from the plant where the additional annual dose for individuals could exceed 20 mSv in the first year after the accident. Within the Special Decontamination Area, the national Government has the responsibility of formulating and implementing remediation plans.
- **Intensive Contamination Survey Area** (Fig. 5.1, right). This area includes those municipalities where the additional radiation dose in the first year was estimated to be between 1 and 20 mSv for individuals in some parts of the municipality[111]. Municipalities conduct monitoring surveys to identify areas requiring decontamination and carry out remediation activities in these areas, with the national Government providing financial and technical support.

In 2012 and 2013, the areas in which evacuation orders had been issued were further subdivided into the following three categories on the basis of the estimated annual total dose to people inhabiting the area, if any (Fig. 5.1, left) [268, 269]:

- **Area 1 (green).** Areas where evacuation orders were ready to be lifted. The estimated annual dose was expected to be 20 mSv or less.

[111] An ambient dose rate of 0.23 μSv/h was used as the radiological criterion for this area. This dose rate corresponds to a conservatively estimated additional effective dose of 1 mSv in one year.

— **Area 2 (orange).** Areas in which residents were still not permitted to live. The estimated annual dose was expected to exceed 20 mSv.
— **Area 3 (red).** Areas to which it was anticipated that residents would not be able to return for a long time. The estimated annual dose was over 50 mSv, and the average annual dose over the period of six years after the accident was expected to be more than 20 mSv.

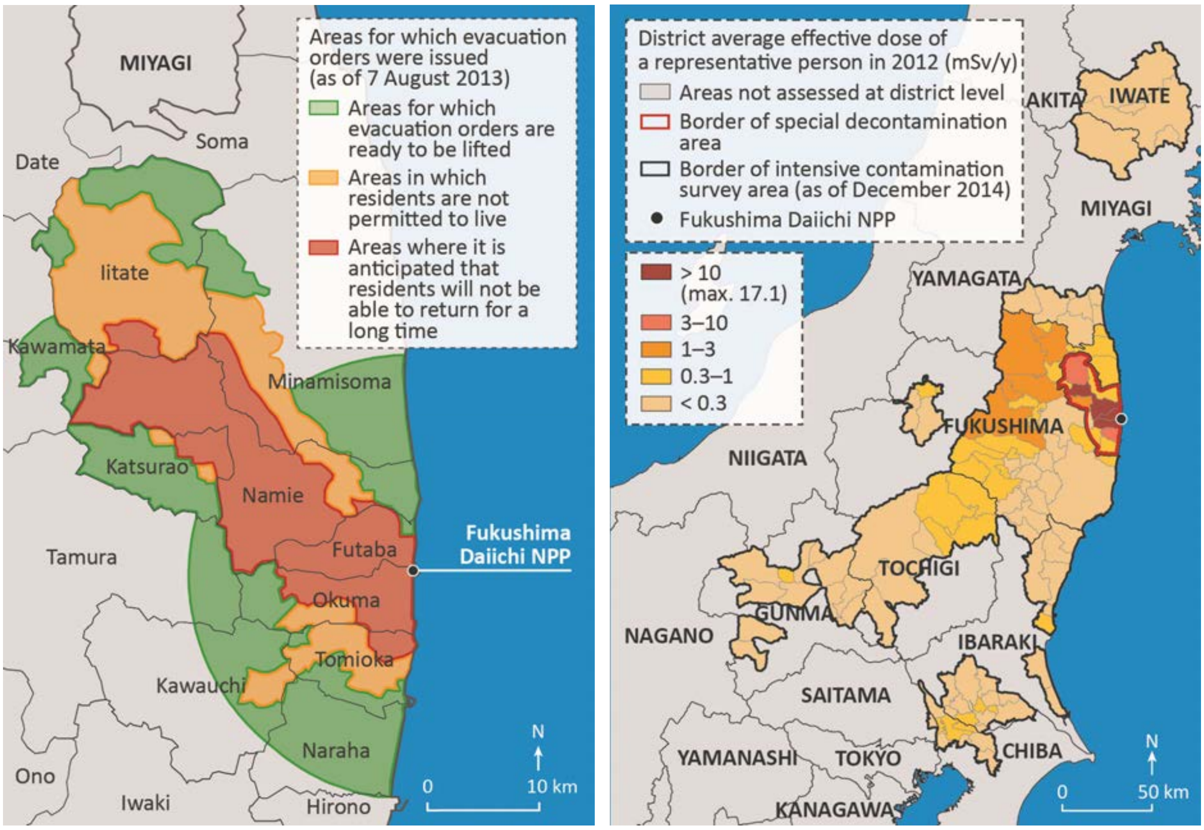

FIG. 5.1. The map on the left shows the subdivision of the evacuation zone as of 7 August 2013 [270]. The map on the right shows the designation of the 'Special Decontamination Area' and the 'Intensive Contamination Survey Area' as of December 2014 and indicates the estimated additional radiation doses of representative persons in 2012.

5.1.3. Progress in remediation

A number of pilot projects were undertaken in 2011. The JAEA initially performed a series of small scale studies at two sites outside the evacuated zones to assess the effectiveness of decontamination in achieving reductions in dose rate for various types of surfaces (e.g. streets, roofs, walls and lawns) [271]. Later studies considered the feasibility of decontamination of larger areas in the evacuated zones, assessed the effectiveness of these measures in reducing ambient gamma dose rates and explored the implications for worker safety and waste management.

These pilot studies played an important role in planning and implementing remediation strategies. They provided information on the effectiveness and applicability of decontamination techniques and helped to establish procedures for the radiation protection of workers [272].

Commonly implemented remediation measures following the Fukushima Daiichi accident are listed in Table 5.1. Topsoil removal, which generates a large amount of waste, was widely used in the first years of remediation.

TABLE 5.1. COMMONLY IMPLEMENTED REMEDIATION MEASURES

Target	Remediation measures
Houses and buildings	Removal of deposits from the roof, deck and gutters Wiping roofs and walls Vacuum sanding High pressure washing
Schoolyards, gardens and parks	Topsoil removal Weed/grass/pasture removal
Roads	Removal of deposits in ditches High pressure washing
Gardens and trees	Mowing Removal of fallen leaves Removal of topsoil High pressure washing Paring tree surfaces
Farmlands	Tillage reversal Topsoil removal Soil treatment (e.g. enhanced application of fertilizer) Soil hardening and removal Weed/grass/pasture removal
Animal production	Control of radiocaesium levels in animal feed
Forests and woodland	Removal of fallen leaves and lower twigs Pruning

Remediation strategies were later implemented in both the Intensive Contamination Survey Area and the Special Decontamination Area, and significant progress was made. By the end of March 2015, decontamination in most parts of the Intensive Contamination Survey Area outside Fukushima Prefecture was almost complete (in about 80% of the municipalities). In the Intensive Contamination Survey Area within Fukushima Prefecture, around 90% of the public facilities, 60% of residential houses and 50% of roads had been decontaminated [273].

Within the Special Decontamination Area, decontamination plans had been completed in four municipalities in March 2015 (Tamura City, Kawauchi Village, Naraha Town and Okuma Town). Decontamination of residential areas had also been completed in two more municipalities (Katsurao Village and Kawamata Town) and had almost been completed in Iitate Village [273]. Most decontamination plans in both decontamination areas 1 and 2 within Fukushima Prefecture were due to be completed before the end of March 2016, although some were due to continue into 2017 (Fig. 5.2).

Investigations performed in residential areas of Tamura and Naraha municipalities showed that ambient gamma dose rates had been reduced by an average of 36% and 46%, respectively. Gamma dose rates (see Box 5.1) were determined by measuring ambient dose rates at a distance of 1 m from the decontaminated surfaces, both before and after remediation actions. Average dose rate reductions in the two municipalities following remedial actions in farmlands, forests and roads were between 21% and 44% [273].

The data indicate that the reduction of ambient gamma dose rates is more significant in areas with higher initial dose rates. After remediation, the gamma dose rates continue to decline owing to the natural processes of weathering and radioactive decay.

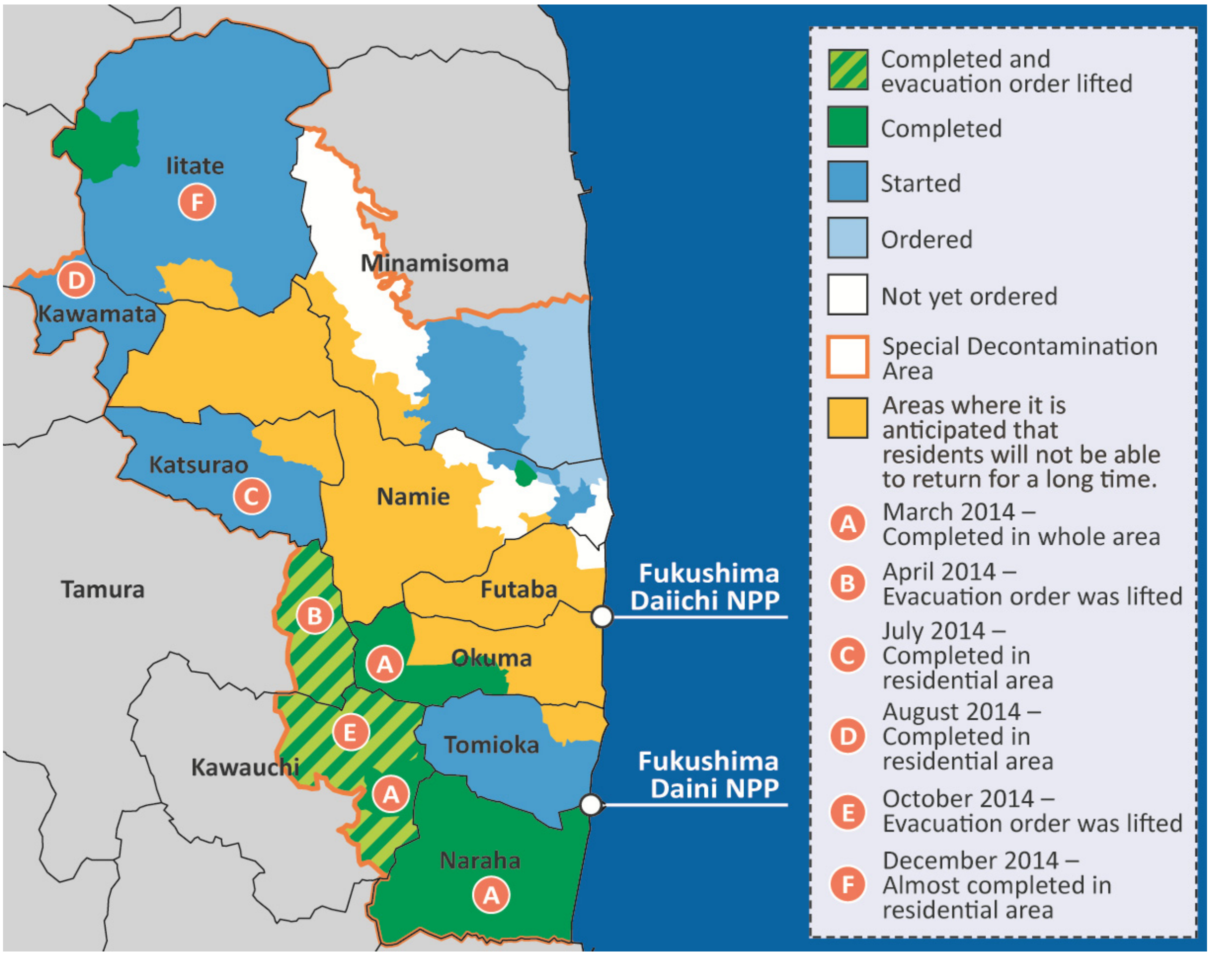

FIG. 5.2. Progress of remediation in the Special Decontamination Area up to December 2014 [273].

Examples of remediation are shown in Fig. 5.3.

Unit costs for decontamination in the Special Decontamination Areas directly controlled by the national Government ranged from around 1100 yen/m^2 (forests) to approximately 5500 yen/m^2 (parks) [274].

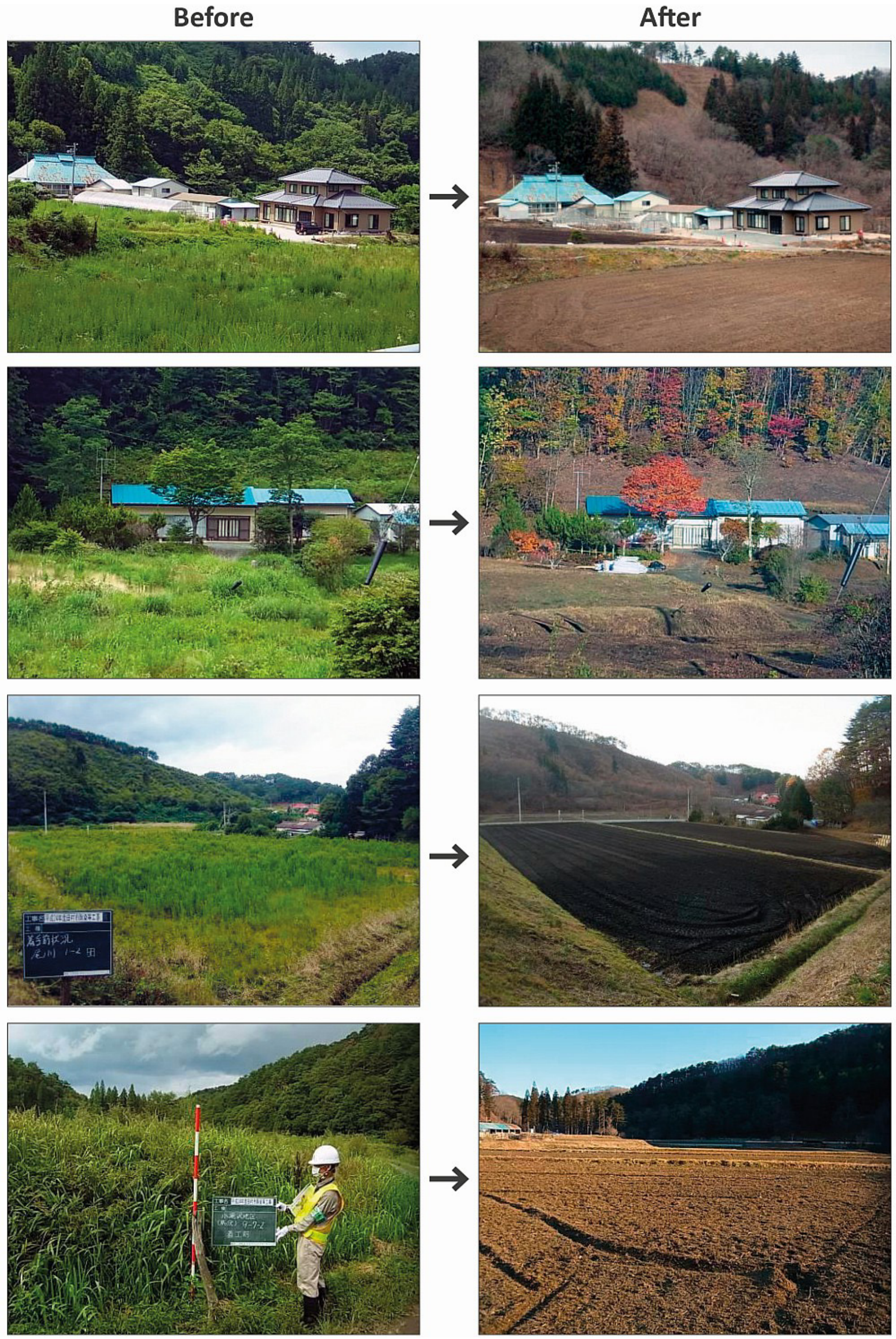

FIG. 5.3. Landscapes before and after remediation in Tamura City (photographs courtesy of Ministry of the Environment, Japan).

5.2. ON-SITE STABILIZATION AND PREPARATIONS FOR DECOMMISSIONING

A comprehensive, high level strategic plan for stabilization and decommissioning of the damaged NPP was developed jointly by TEPCO and the relevant Japanese Government agencies. The plan was first issued in December 2011 and subsequently revised to reflect the experience gained and an improved understanding of the conditions of the damaged NPP, as well as the magnitude of the future challenges. The strategic plan addresses the complex nature of on-site work and includes: the approach to ensure safety; measures towards decommissioning; systems and environments to facilitate the work; and research and development requirements.

At the time of writing, safety functions had been re-established and structures, systems and components were in place to reliably maintain stable conditions. However, there was a continuing need for control of ingress of groundwater to the damaged and contaminated reactor buildings. The resulting contaminated water was being treated to remove radionuclides to the extent possible and stored in more than 800 tanks. More sustainable solutions are needed, considering all options, including the possible resumption of controlled discharge into the sea. Final decision making will require engaging relevant stakeholders and consideration of socioeconomic conditions in the consultation process, as well as implementation of a comprehensive monitoring programme.

Plans for the management of spent fuel and fuel debris were developed and removal of fuel from spent fuel pools began.[112] A conceptual model of future activities for removing fuel debris was also developed, which takes account of the many preliminary steps required, including visual confirmation of the configuration and composition of the debris. The high radiation dose levels in the damaged reactors meant that no such confirmation had been possible at the time of writing.

Japanese authorities have estimated that the timescale for completing decommissioning activities is likely to be in the range of 30–40 years. Decisions regarding the final conditions of the plant and site will be the subject of further analysis and discussions.

Box 5.2. Stabilization and post-accident decommissioning

The term 'decommissioning' refers to the administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility.

In practical terms, decommissioning is the progressive removal of the facility's structures, systems and components. Under normal circumstances, decommissioning of an NPP is a planned activity that is initiated after the decision has been taken to end operations. Post-accident decommissioning presents a different set of challenges: the condition of the facilities and the status of the fuel and the plant equipment need to be first determined and a path forward decided. This may require development of new technologies and methodologies.

If reactor shutdown is the consequence of an accident, the facility needs to be brought to a safe configuration (stabilization) before an approved final decommissioning plan is put into effect. Stabilization comprises actions required to ensure that the plant structures (such as the buildings that house the damaged reactors), systems (such as electrical supply systems) and components (such as pumps or motors) are put in a stable condition and can operate for as long as may be required.

[112] Removal of fuel from the Unit 4 spent fuel pool was completed in December 2014.

5.2.1. Strategic plan

Following the emergency phase, TEPCO and the relevant government agencies established a strategic plan — the 'Mid-and-Long-Term Roadmap towards the Decommissioning of Fukushima Daiichi Nuclear Power Station Units 1–4' — for stabilization and decommissioning activities [275]. The plan was first issued in December 2011 and subsequently revised to take account of the greater experience and improved understanding of the on-site conditions [276].[113] It is a comprehensive, high level strategic plan for those supervising the recovery. Decommissioning is projected to be completed on a timescale of 30–40 years, according to Japanese authorities' estimates.

The plan describes the strategic approach for areas of work concerning:

- **The approach to ensuring safety**, which includes strategic objectives for reducing risks and optimizing the removal of fuel and fuel debris.
- **Mid-term and long term measures towards decommissioning**, which include plans for the removal of fuel and fuel debris from each reactor unit. These plans are sufficiently flexible to address the possible range of conditions that may be revealed as more information is gained in the processes of removing fuel and fuel debris.
- **Systems and environment to facilitate work**, for which TEPCO established an organization for the centralized monitoring of the health and radiation exposure of workers. Efforts to improve radiation protection of workers continued, and plans were put in place for managing and ensuring the availability of a trained workforce throughout the decommissioning process.
- **Research and development**, which is necessary, as much of the work to be accomplished at the Fukushima Daiichi NPP is the first of its kind, requiring equipment and technology that has yet to be developed or used on a large scale. The International Research Institute for Nuclear Decommissioning was established to develop technologies for nuclear decommissioning, promote cooperation with international and domestic organizations on nuclear decommissioning, and develop human resources for research and development.

5.2.2. Preparations for decommissioning

Shortly after its establishment [278], the NRA developed a new regulatory framework for the regulation of so-called disaster experienced facilities, which need special measures to prevent further accidents and to ensure nuclear security. On 7 November 2012, the NRA designated the Fukushima Daiichi NPP as 'Specified Reactor Facilities', which are facilities where a nuclear accident has occurred and special regulations commensurate with the prevailing conditions at the facility are stipulated.

This designation allowed the NRA to require TEPCO to develop a plan to implement the actions outlined in the strategic plan [275]. TEPCO's Implementation Plan was submitted in December 2012 [279] and was subsequently approved. TEPCO is responsible for carrying out the actions specified in the Implementation Plan. The execution of these actions is reviewed by the NRA.

Additionally, the NRA developed a regulatory requirement for managing the additional effective dose at the site boundary in February 2014 and identified actions in 'Measures for Mid-term Risk Reduction at TEPCO's Fukushima Daiichi NPS' in February 2015 [280].

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[113] It is anticipated that there will be further revisions to the Roadmap as plans are adapted in response to changing conditions and new information. The third revision of the Roadmap was issued during the final preparation of this report (June 2015). This modified the schedule for and the approach to fuel and debris removal and refined approaches to risk reduction, communication with local stakeholders, reduction in workers' exposures, and management of research and development [277].

TEPCO established stable conditions at the site to maintain protection and safety and allow progress towards decommissioning [275]. Important support functions, such as normal and backup electrical supplies, were re-established and upgraded. Fundamental safety functions were also re-established. Arrangements to ensure the long term reliability of stable conditions include:

- Monitoring plant conditions;
- Cooling the fuel and fuel debris;
- Maintaining nuclear subcriticality;
- Controlling levels of hydrogen;
- Ensuring structural stability of the reactor buildings;
- Controlling water ingress to the reactor buildings and preventing leakage to the environment;
- Ensuring essential electrical power supplies;
- Ensuring the fulfilment of fundamental safety functions over the long term.

Important safety functions were re-established and upgraded, for example, by installing multiple backup features and replacing and/or upgrading mobile and temporary systems to augment permanent ones. The situation on the site remains complex, and careful monitoring and control is required to ensure continued stable conditions.

5.2.3. Management of contaminated water

Water that enters damaged reactor buildings becomes contaminated and poses a particularly challenging problem due to the large volumes involved. At the time of writing, water continued to enter the reactor buildings at the Fukushima Daiichi NPP in two ways: water injection into the reactor cores for cooling purposes and ingress of groundwater. Characterizing and managing this water continued to be necessary (Fig. 5.4).

Before the accident, groundwater flowing from the mountainside to the rear of the Fukushima Daiichi NPP was pumped at a rate of approximately 850 m^3/d from sub-drains located around the buildings of Units 1–4 to control the groundwater level. As a consequence of the accident, the sub-drains and pumps that previously suppressed building buoyancy and prevented groundwater from entering the buildings ceased operation [281].

After the accident, approximately 400 m^3/d of uncontaminated groundwater flowed into the buildings. Approximately 400 m^3/d of water is circulated through the Unit 1–3 reactors for cooling. The groundwater that enters the buildings is mixed with the circulating water used for cooling the reactors, leading to a total volume of approximately 800 m^3/d of contaminated water that has to be managed. Approximately 400 m^3/d of this water is re-injected into the reactors for cooling the fuel and fuel debris, and the remaining 400 m^3/d is stored in the contaminated water storage tanks [276].

The water is treated to remove radionuclides, with the exception of tritium, which cannot be removed [282]. The treated water was stored on the site in 826 tanks (as of 12 February 2015) [283].

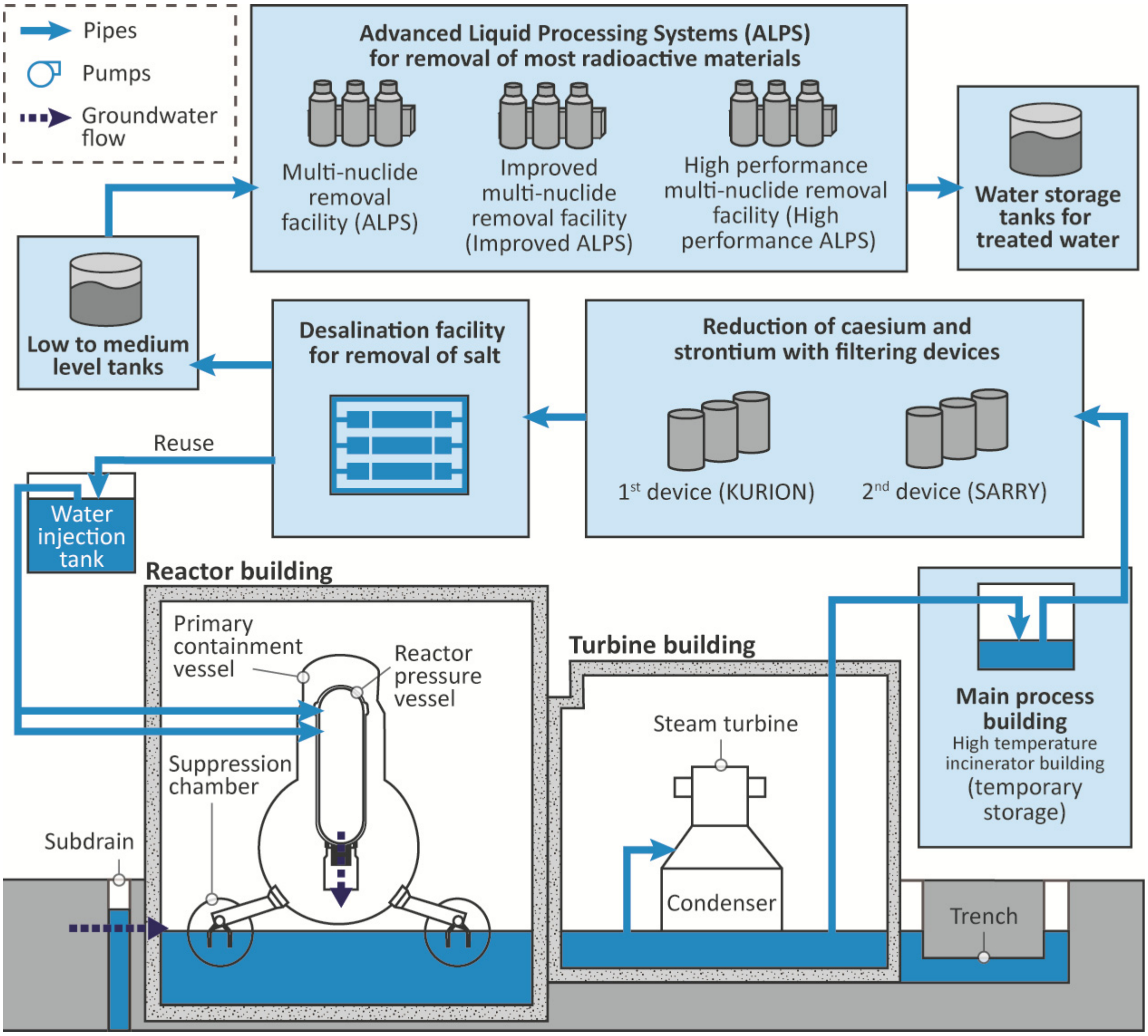

FIG. 5.4. Management of contaminated water on the site [284].

Various water management techniques have been deployed, or were being planned, including the improvement and installation of additional treatment systems and storage tanks, the restoration of the sub-drain system and the installation of seaside impermeable walls. Uncontaminated groundwater from uphill of the damaged facilities is being bypassed around the facilities and into the ocean (Fig. 5.5) [285]. In addition, a cryogenic 'frozen' wall on the mountain side of the reactor buildings was under construction to prevent further water ingress. A cryogenic wall on the sea side of the reactor buildings was also planned.

With the approval of the NRA and the acceptance of the relevant stakeholders, including Fukushima Prefecture and the fishing industry, TEPCO began discharging the bypassed uncontaminated groundwater directly into the sea in May 2014 [285]. This measure reduced the volume of water requiring treatment.

The large quantities of contaminated water on the site present a variety of risks. Owing to malfunctions of tanks, pipes and valves, or during heavy rainfall, leaks of radioactively contaminated water from components were observed. In some cases, the leaks led to releases of radionuclides into the sea. The identification of such leaks triggered more intensive monitoring, both on the site as well as in the marine environment [287]. Although measures were being implemented to stop or reduce the leakage, more sustainable solutions are needed, considering all options, including the possible resumption of controlled discharges into the sea. As a result of the IAEA Review Missions [288, 289], TEPCO was advised to perform an assessment of the potential radiological impact of the release of water containing tritium and any other residual radionuclides into the sea. It was also recognized that final decision making would require engaging all stakeholders, including TEPCO, the NRA, the national Government, the Fukushima Prefecture government, local communities and others, and that there was a need to consider socioeconomic conditions in the consultation process and to implement a comprehensive monitoring programme to ensure that there was no detrimental impact on human health and the environment [288, 289]. In this context, further guidance on the application of international guidance for discharges in post-accident situations would be beneficial.

FIG. 5.5. Illustration of water management efforts. Storage tanks for contaminated water are shown on the left [286].

5.2.4. Removal of spent fuel and fuel debris

The preparation for decommissioning the accident damaged facilities includes the removal of spent fuel and new fuel assemblies from storage pools inside the damaged reactor buildings. TEPCO began removing the fuel in the storage pool inside the Unit 4 reactor building to the common fuel pool in November 2013. The operation was completed in December 2014 [290].

It will require several years to remove the spent fuel and new fuel assemblies from the storage pools in Units 1–3. A more accurate estimate of the time needed is dependent on the progress in removing the debris resulting from the explosions, preparing the upper structure of Units 1–3 for access, providing supports for equipment and structures for removal, and other measures. The spent fuel will be placed in a common pool for temporary storage.

Removal and management of debris from the melted fuel in the reactor core is a much more complex challenge. Visual confirmation of the configuration and the composition of the damaged fuel ('fuel debris') resulting from the accident has not been possible due to the high radiation dose levels in the damaged reactors. Available analyses indicate that most of the fuel in Unit 1 melted and that some penetrated the bottom of the reactor pressure vessel to the primary containment vessel, whereas in Units 2 and 3, fuel also melted, but a greater proportion remained within the reactor pressure vessels [9].

At the time of writing, the Government of Japan was sponsoring conceptual studies on ways of gaining access to and removing fuel debris [276, 291]. A conceptual model for future activities for removing fuel debris has been developed, which takes account of the many preliminary steps required, including:

(1) **Reduction of radiation levels in the reactor buildings**. Access by workers to the spaces inside the reactor buildings is difficult because of high dose rates and rubble and contaminated dust that have been scattered inside them. Decontamination, in many instances with remotely operated equipment, will be needed to make access possible.
(2) **Repair of the primary containment vessels containing water**. An investigation will be conducted and the required equipment will be developed to stop water leakage from the containment vessels, after which the water levels will be monitored and maintained as needed for subsequent operations.
(3) **Characterization of the conditions inside the primary containment vessels**. Removal of the fuel debris requires determining the exact locations of the pieces of fuel debris. Equipment to investigate the conditions inside the containment vessels will be developed and the necessary information, such as the locations, distributions and shapes of the pieces of fuel debris, will be obtained.
(4) **Characterization of the conditions inside the reactor pressure vessels**. This includes the distribution of fuel debris, levels of radioactivity and the physical configuration of the damaged pressure vessels.
(5) **Development of technologies for the removal of fuel debris**. The preconditions for removal of fuel debris will be identified, leading to the development of technologies and equipment to open the reactors, remove structural impediments inside the reactor pressure vessels and remove fuel debris.
(6) **Water management.** Beyond cooling and boron control, careful water management will be necessary as the approach to the removal of fuel debris progresses. For example, additional means will be needed for removal of particulate material that becomes suspended in water as a result of the removal operations.
(7) **Packaging, transfer and storage of fuel debris**. As debris is removed from the reactor pressure vessels and the primary containment vessels, it will need to be placed in shielded containers. The

containers will need to be removed from the reactor buildings and placed in interim storage on the Fukushima Daiichi site until a final decision on their disposition has been taken.

(8) **Prevention of nuclear criticality of fuel debris**. Evaluations will be conducted and monitoring techniques put in place to preclude any possibility of nuclear criticality within the debris.

(9) **Accounting for, and control of, nuclear material in the fuel debris**. Accountability is required for fissionable material, in conformity with the safeguards agreement between Japan and the IAEA and with Japanese domestic law. Because the standard methods cannot be applied to the fuel debris, accountability measures will be established before the fuel debris is removed from the reactors.

Fuel debris will be removed while submerged in water to provide shielding and to minimize radioactive releases to the air. The high levels of radiation and contamination, and the unknown distribution and properties of the fuel debris, mean that much of the work will need to be conducted by use of remotely operated equipment. Strategies for removal of fuel debris will need to be adjusted as data become available regarding the conditions of the fuel and fuel debris, as will plans to design, engineer and build appropriate equipment.

5.2.5. Decommissioning end state for the site

Under normal (non-accident) circumstances, the end state of an NPP is defined and described in the licence application and subsequent supporting documents. Two strategies for achieving a plant end state are generally available: immediate dismantling and deferred dismantling, which is sometimes referred to as safe storage. Under exceptional circumstances, for example following a nuclear accident, entombment may also be considered [292].

A nuclear accident may invalidate prior decommissioning planning owing, for example, to the need to stabilize structures, systems and components before the new decommissioning plan can be developed. Decommissioning plans, removal of the fuel debris and options for the final end state of the site depend on the nature of the accident and will include consideration of the status of: nuclear residues, particles and radioactive materials remaining within the facilities; spent fuel and fuel debris in storage; and solid radioactive waste and processed water in storage [293]. The interests of stakeholders, obtained, for example, through an appropriate public consultation process, will also influence the planning and execution of the decommissioning.

It is currently not possible to predict the end state of the Fukushima Daiichi NPP [291]. It may be noted that none of the three plants elsewhere in the world that experienced the most severe fuel damage in previous accidents has yet achieved the final end state for complete decommissioning [293] (Box 5.3).

Box 5.3. Status of decommissioning of damaged nuclear facilities

The three facilities elsewhere that have experienced the most severe fuel damage in previous accidents are Windscale (United Kingdom), Three Mile Island (United States of America) and Chernobyl (former Soviet Union). Their status at the time of writing was as follows:

The Windscale pile, damaged in an accident in 1957, was in a care and maintenance condition, with a plan to place it in safe storage in the next few years and with final decommissioning planned to occur around 2050.

The unit damaged at the Three Mile Island NPP in 1979 was in a safe storage mode, with a plan for complete dismantlement and site remediation within the next 20 years.

Chernobyl Unit 4, severely damaged in the accident in 1986, was in the process of being placed in a condition of safe storage, with final decommissioning projected for around 2050.

A final decision on the end state to be achieved at the Fukushima Daiichi site will need to consider many factors, including the future use of the land, possible radiation doses to the decommissioning workers, the waste that would be generated and options for the waste conditioning and disposal.

5.3. MANAGEMENT OF CONTAMINATED MATERIAL AND RADIOACTIVE WASTE

Stabilization of a damaged NPP and the on-site decontamination and remediation efforts in the surrounding areas result in large quantities of contaminated material and of radioactive waste. On the site, large amounts of contaminated solid and liquid material, as well as radioactive waste, have been generated following various recovery activities.[114] The management of such material — with its varying physical, chemical and radiological properties — is complex and requires significant efforts.

Following the Fukushima Daiichi accident, there were difficulties in establishing locations to store the large amounts of contaminated material arising from off-site remediation activities. Several hundred temporary storage facilities had been established in local communities. Efforts to establish an interim storage facility were continuing.

5.3.1. Managing the waste

A large amount of waste (known as 'disaster waste') was generated by the earthquake and tsunami, some of which was contaminated (predominantly by ^{134}Cs and ^{137}Cs) as a result of releases from the Fukushima Daiichi NPP. On-site stabilization activities have increased the inventory of contaminated material and of solid and liquid radioactive waste necessitating management, while off-site remediation activities have increased the amount of contaminated material.

Box 5.4. Radioactive waste

Radioactive waste is material for which no further use is foreseen that contains radionuclides with a content or concentration above a specified level. Disposal is the internationally recognized end point for the management of radioactive waste. However, storage of some radioactive waste for periods of tens of years is often necessary while disposal facilities are being developed. Certain types of radioactive waste (low level radioactive waste) can be disposed of in 'near surface' waste disposal facilities.

The management (i.e. pretreatment, treatment, conditioning, transport, storage and future disposal) of large amounts of waste with differing physical, chemical and radiological properties presents a challenge. Equipment, activities and facilities have had to be developed and/or modified under circumstances made more difficult by the loss of infrastructure caused by the earthquake and tsunami and by high radiation levels. Amendments to legislation and to the national approach to waste management were also necessary [124, 266, 278, 294].

5.3.2. Off-site activities

Off-site remediation was initiated with the objective of reducing external exposures. The remedial actions included the removal of topsoil and vegetation and the decontamination of public and residential areas. The size of the area requiring remediation was influenced by the radiological criteria

[114] The distinction between contaminated material and radioactive waste depends upon the radionuclides and the activity concentrations associated with the materials.

and action levels adopted, which also had implications for the amount of contaminated material requiring management.

In general, a low reference level results in the generation of a larger amount of contaminated material. It is estimated that the stockpile of soil and other contaminated material generated from remediation activities after the accident will be approximately 16–22 million m^3 after the reduction in volume by incineration of plants and trees [273].

The stages of the waste management process used in Fukushima Prefecture are illustrated in Fig. 5.6. The management of waste generated in the remediation activities involves its collection in temporary storage facilities near the locations for decontamination. Many hundreds of temporary storage facilities have been constructed. After temporary storage, this waste will be transported into the interim storage facility. Some of the material has contamination at levels that are sufficiently low to allow the use of existing infrastructure for the disposal of municipal solid waste (e.g. municipal incinerator facilities and waste landfills). However, the process of obtaining the agreement of municipalities to use conventional incinerators to reduce the volume of off-site contaminated material has proved to be difficult.

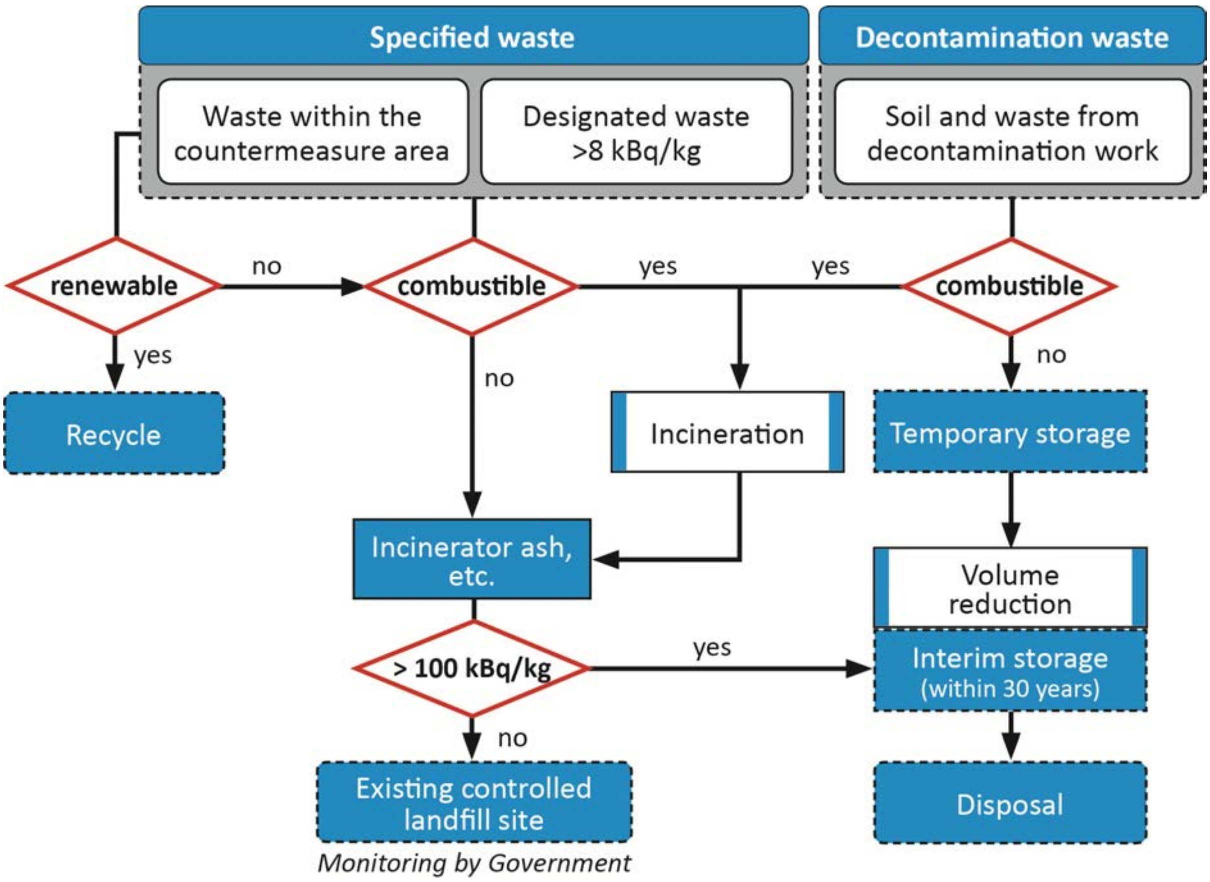

FIG. 5.6. Flow chart for the management of specified waste and decontamination waste in Fukushima Prefecture [295].

There were delays in site selection for temporary and interim storage facilities. Obtaining the agreement of the local population has been a contributing factor in the siting delays. However, following discussions of national and local government officials with local residents and landowners, the plan to construct an interim storage facility was accepted in Okuma Town in December 2014 and in Futaba Town in January 2015. In January 2015, the Ministry of the Environment (MOE) confirmed plans and arrangements for pilot-scale transport of contaminated soil to the interim storage facility from March 2015 [273]; for testing purposes, these transports started on 13 March 2015.

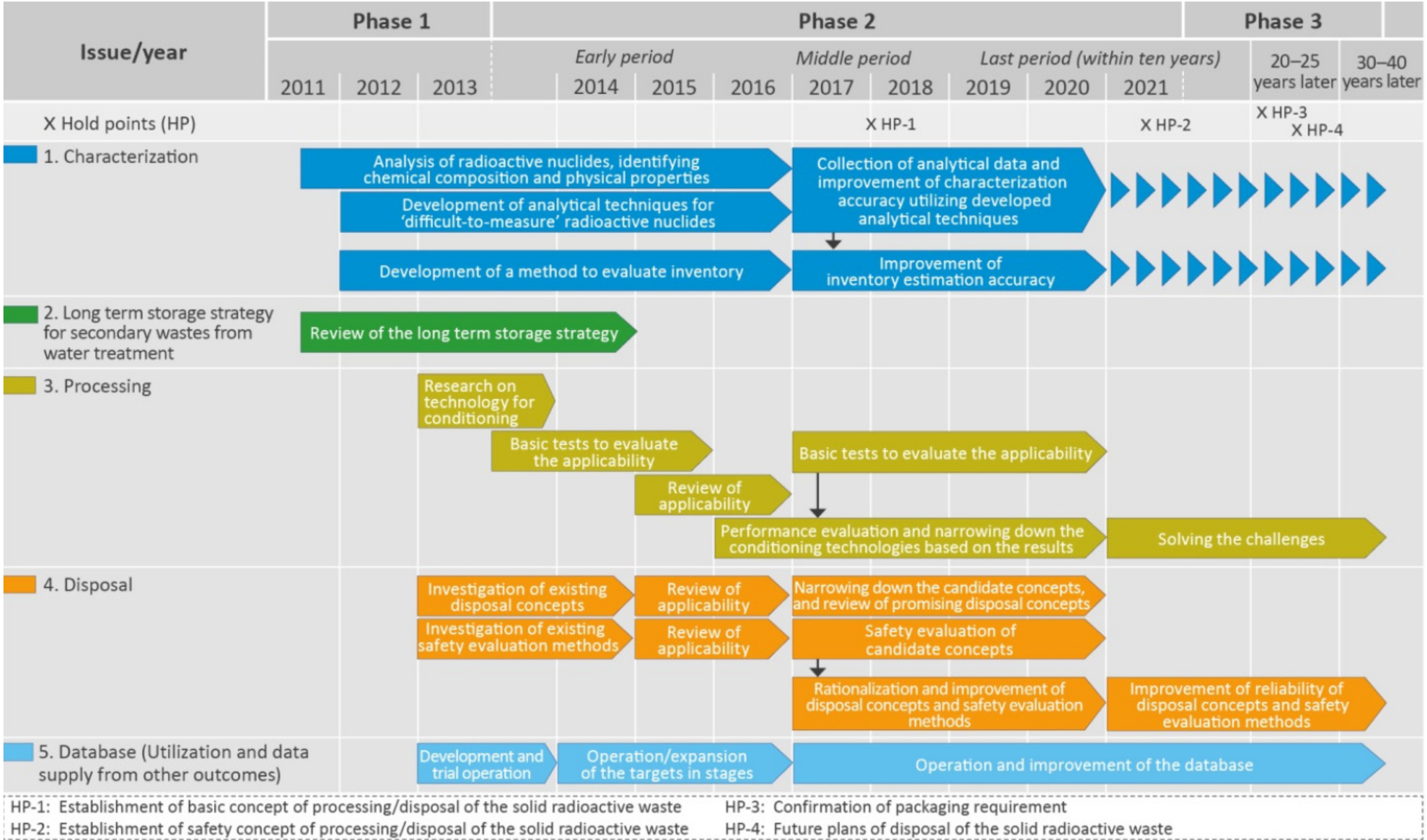

FIG. 5.7. Part of the strategy for on-site waste management [291].

5.3.3. On-site activities

At the Fukushima Daiichi NPP, large amounts of contaminated solid and liquid material as well as radioactive waste have been generated following various recovery activities. For example, as of 30 November 2014, 131 900 m^3 of debris and 79 700 m^3 of trees were being stored on the site [296, 297]. The generation of these large amounts of contaminated material and radioactive waste has required the establishment of effective strategies for waste management. In particular, there has been a need to develop facilities for treatment and storage of many hundreds of thousands of cubic metres of contaminated and treated water as well as for solid waste resulting from the treatment processes and the clearing of large areas of land. Part of the strategy for on-site waste management, including the facilities for water treatment and storage, is illustrated in Fig. 5.7.

There is a continuing need for storage capacities for various types of solid and liquid waste streams (Fig. 5.8). Consequently, volume reduction has become an important component in the management of on-site waste, for example through waste avoidance, installation of incinerators, and reuse and recycling of materials. Additional waste is expected from the decommissioning of the NPP [298]. The types and amounts of waste will depend on the approach adopted.

FIG. 5.8. Aerial view of the on-site area showing the water storage tanks [301].

There have been efforts to move radioactive waste away from the site boundary in order to limit dose rates at the boundary to less than 1 mSv/year. These activities have no impact on public exposure as there is no public presence at the site boundary [299].

The management of waste on the site poses many complex challenges, requiring further research and development. As new capabilities are obtained, a strategy for final disposal of on-site waste will need to be considered, involving decisions for both the near term and the long term [300].

5.4. COMMUNITY REVITALIZATION AND STAKEHOLDER ENGAGEMENT

The nuclear accident and radiation protection measures introduced in both the emergency and post-accident recovery phases have had significant consequences for the way of life of the affected population. Evacuation and relocation measures and restrictions on food involved hardships for the people affected. The revitalization and reconstruction projects introduced in Fukushima Prefecture were developed from an understanding of the socioeconomic consequences of the accident. These projects address issues such as reconstruction of infrastructure, community revitalization and support and compensation.

Communication with the public on recovery activities is essential to build trust. To communicate effectively, it is necessary for experts to understand the information needs of the affected population and to provide understandable information through relevant means. Communication improved in the aftermath of the accident, and the affected population became increasingly involved in decision making and remediation measures.

The accident and the protective actions introduced in both the emergency phase and the recovery phase impacted the way of life of populations in the areas affected. By 30 January 2015, the number of evacuees was around 119 000, compared with a peak of around 164 000 in June 2012. The hardships associated with evacuation, relocation and restrictions on food are substantial [268, 269].

The earthquake, the tsunami and the accident resulted in the destruction, degradation or disuse of infrastructure (including schools, hospitals and commercial enterprises), had an impact on business and trade, and brought about demographic changes through the evacuation of large numbers of people. It was reported that young families were more likely to remain evacuated, and the elderly were more likely to return to their homes [302]. Recovery and revitalization plans at the national and local levels recognize the importance of physical and socioeconomic reconstruction and address issues such as reconstruction of infrastructure, community support and compensation [269].

The particular challenges for people living in temporary accommodation include a range of issues of general physical and mental well-being that are associated with high levels of unemployment and the difficulties associated with provisional accommodation [239]. The total number of evacuees living in temporary accommodation as a result of the earthquake, tsunami and nuclear accident is not known precisely but, by June 2013, 16 800 temporary housing units had been constructed and nearly 24 000 families were living in accommodation rented by the prefectural government [269]. In addition, there were plans to build 2586 units of permanent public housing by 2015 for people affected by the earthquake and tsunami. For those evacuated in the response to the accident, 4890 units of permanent public housing were planned [283].

5.4.1. Socioeconomic consequences

Evacuation resulted in the loss of farms and businesses. Fishing ceased within 30 km of the site (reduced to 20 km at the end of September 2011). Agricultural and other commercial activities have ceased in an area of about 700 km^2 outside the Special Decontamination Area [269, 303, 304].

Socioeconomic consequences in the agricultural sector and other enterprises were also seen outside the Special Decontamination Area and the Intensive Contamination Survey Area. In addition to the loss of employment and of livelihoods for those affected, restrictions on food, export losses involving food and consumer goods, the costs of monitoring to demonstrate compliance with radiological criteria and the payment of compensation to people affected have also had an effect. Indirect socioeconomic consequences include those arising from the loss of consumer confidence, not only in food products, but also in commodities from and businesses in the affected areas [269, 303, 305].

The combination of earthquake, tsunami and nuclear accident had a direct effect on the Japanese economy. Exports fell by 2.4% in April 2011 compared with the level in April 2010. At the same time, imports increased, especially those of fuels, chemicals and food, resulting in a deficit in the trade balance in April and May 2011 [303]. Imports of fossil fuel remained at a higher level at the time of writing [306].

Although at the time of the accident Japan was not party to any of the conventions on civil liability for nuclear damage (it joined the Convention on Supplementary Compensation for Nuclear Damage (CSC) on 15 January 2015), legislation enacted in 1961 was consistent with the basic principles of nuclear liability as embodied in those conventions. Under this legislation, TEPCO was exclusively liable for nuclear damage caused by the Fukushima Daiichi accident [307]. Its liability was unlimited in amount. Following the accident, TEPCO was not granted exemption from liability by the Government and Parliament on the assumption that the exemption clause related to a grave natural disaster, as specified in the Act on Compensation for Nuclear Damage, was inapplicable in this case. Various means to allow TEPCO to meet its obligations towards the victims of the accident have been implemented, including provisional compensation payments as an emergency measure, the provision of financial support to TEPCO by the Nuclear Damage Compensation and Decommissioning Facilitation Corporation (NDF), and NDF becoming the controlling shareholder of TEPCO. Moreover, the creation of the Dispute Reconciliation Committee for Nuclear Damage Compensation and the issuance of legally non-binding guidelines provided a mechanism for prompt out of court settlements of compensation for nuclear damage.

The established compensation policy applies to those ordered to evacuate and also covers impacts on livelihood and way of life, loss of profits due to restrictions and loss of trust by consumers, and infrastructure changes for people remaining in the area. In addition, there are specific provisions for parents with young families and for pregnant women [308].

According to guidelines established in December 2011, people subject to evacuation received compensation of the order of 100 000 yen per person and per month. Additional compensation of about 900 000 yen per person will be paid to those returning to live in the areas affected within a year after the lifting of the evacuation order [309].

5.4.2. Revitalization

A number of initiatives to stimulate the revitalization of Fukushima Prefecture have been implemented with government and local support. These include the reconstruction of infrastructure, housing and transport. Some actions focus on regaining consumers’ trust in products, while also promoting local pride and tourism. Recognizing that the availability of work and employment is also a driving factor for the return of residents (or for the settlement of new populations), other initiatives focus on rebuilding businesses as well as creating new commercial opportunities.

Revitalization initiatives and reconstruction activities linked to recovery range from those at the national Government level to initiatives by non-governmental organizations and local communities. The Government of Japan established a Reconstruction Agency; Fukushima Prefecture has initiated various activities including the establishment of the Centre for Environmental Creation [234, 269];

and the Fukushima Revitalization Headquarters was set up by TEPCO in 2013. All projects aim to combine radiation protection actions with broader societal aspects, such as the revitalization of infrastructure and public engagement and — in the case of the Revitalization Headquarters — compensation [310].

The actions vary across the prefecture, often depending on the engagement of local leaders and the different challenges within the region. Examples of successful revitalization initiatives include cooperation between peach growers and distributors and the food industry to restore public trust in food produced in Fukushima Prefecture [269, 311].

5.4.3. Engagement of and communication with stakeholders

Engagement of stakeholders has increased and strategies for consultation and involvement have improved as remediation and recovery actions have progressed. The response to the accident has provided a number of examples that show the benefits of involving affected populations in activities for recovery, from consultation and dialogue to remediation actions (so-called self-help actions).

Open and effective communication with the public is an essential part of revitalization. An information hub for the area on decontamination (Decontamination Information Plaza) was opened in Fukushima City in January 2012 as a joint project of Fukushima Prefecture and the MOE [312].

Other communication activities at the local level include dialogues between experts and the public and specific advice for self-help actions. These activities have helped to restore communication with Fukushima residents and to rebuild trust.

A flow chart of the implementation process for remediation and associated interactions with stakeholders is shown in Fig. 5.9. All steps in the development of plans and their implementation included stakeholder participation and consultation. In the case of remediation of privately owned land, agreement is required from the landowners before any remediation activities can be started.

In a nuclear accident, the media, in both traditional and new forms, play an important role in communicating with the public. The Fukushima Daiichi accident was characterized by a high level of media coverage, through the Internet, social media and, in the initial phase, continuous television and radio broadcasts. The coverage of the accident lasted for several months, focusing mainly on problems linked to the accident site, but also on the protective actions taken by Japanese authorities. Social media intensified reporting on the event, as well as disseminating the views of individuals and non-governmental organizations. A considerable amount of information was available, of varying quality and levels of credibility [310].

Radiation safety experts needed to learn what kind of information the public was requesting and to provide it in an understandable manner. Critical questions asked by the affected communities and by the media focused on what levels of radiation are ‘safe’ [314].

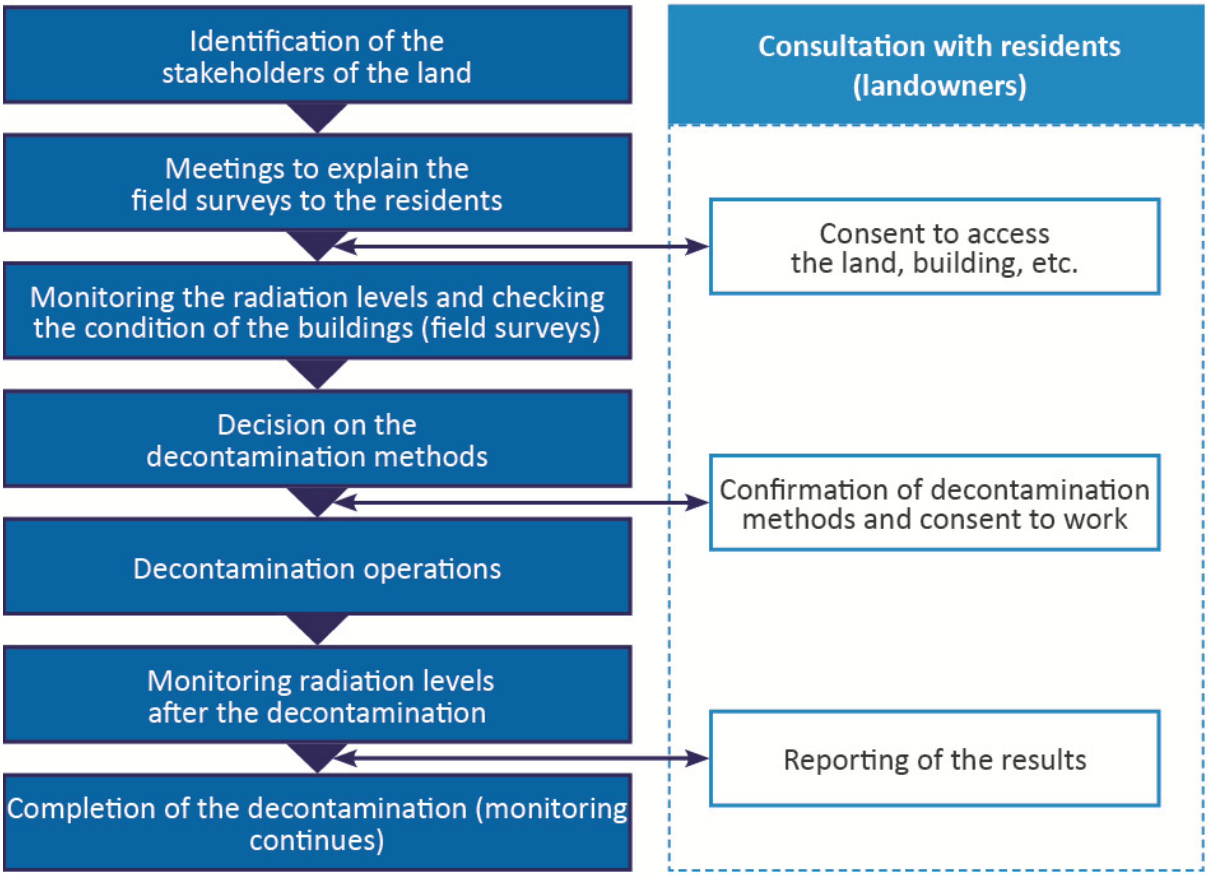

FIG. 5.9. Flow chart of the process for remediation and for consultation with residents [313].

5.5. OBSERVATIONS AND LESSONS

A number of observations and lessons have been compiled as a result of the assessment of the post-accident activities.

— **Pre-accident planning for post-accident recovery is necessary to improve decision making under pressure in the immediate post-accident situation. National strategies and measures for post-accident recovery need to be prepared in advance in order to enable an effective and appropriate overall recovery programme to be put in place in case of a nuclear accident. These strategies and measures need to include the establishment of a legal and regulatory framework; generic remediation strategies and criteria for residual radiation doses and contamination levels; a plan for stabilization and decommissioning of damaged nuclear facilities; and a generic strategy for managing large quantities of contaminated material and radioactive waste.**
These strategies and measures need to include:
- The establishment of a legal and regulatory framework that specifies the roles and responsibilities of the various institutions to be involved. This framework needs to address off-site remediation, on-site stabilization and preparations for decommissioning, management of contaminated material and radioactive waste, and community revitalization and stakeholder engagement.
- Generic remediation strategies and criteria (reference and derived action levels) for residual radiation doses and contamination levels.
- A plan for the stabilization of conditions on the site of a damaged nuclear facility and preparations for its decommissioning.

- Development of a generic strategy for managing large quantities of contaminated material and radioactive waste, supported by generic safety assessments for storage and disposal facilities.
- Sufficient flexibility to ensure that the management of post-accident conditions can be adapted in response to changing conditions and acquired information and experience.

— **Remediation strategies need to take account of the effectiveness and feasibility of individual measures and the amount of contaminated material that will be generated in the remediation process.**

Having established reference levels for residual radiation doses and contamination levels, it is essential to control carefully the amount of contaminated material generated by implementing the remediation strategy in order to minimize the amount of waste to be managed. The absence of preparations for recovery from a nuclear accident in Japan meant that, initially, large volumes of potentially contaminated material were generated. As time elapsed and planning developed, remediation actions were optimized, leading to improved control of the amount of waste to be managed.

Pilot projects were useful in determining both the effectiveness of particular remediation techniques and the amount of waste generated by particular techniques. Pilot projects also contributed to establishing procedures for the radiation protection of workers.

— **As part of the remediation strategy, the implementation of rigorous testing of and controls on food is necessary to prevent or minimize ingestion doses.**

The systematic implementation of rigorous testing of and controls on food after the accident demonstrated that ingestion doses can be kept at low levels.

To establish confidence in locally produced food, local monitoring stations were set up to allow people in affected areas to bring food to be measured. This control of ingestion doses simplified the recovery by allowing remediation to focus on techniques that reduce external doses.

— **Further international guidance is needed on the practical application of safety standards for radiation protection in post-accident recovery situations.**

Further practical guidance is needed on the application of the IAEA safety standards in existing exposure situations. The reference levels adopted for the early post-accident years need to be periodically reviewed and modified, as appropriate, in response to the changing radiological conditions. The guidance needs to include a methodology for the selection of case and site specific reference levels, in terms of dose and derived quantities, as well as mechanisms to integrate technical and scientific advice with other socially relevant factors to establish a coherent, transparent and collectively accepted decision making process.

— **Following an accident, a strategic plan for maintaining long term stable conditions and for the decommissioning of accident damaged facilities is essential for on-site recovery. The plan needs to be flexible and readily adaptable to changing conditions and new information.**

Preparations for the decommissioning of a facility damaged in an accident would first involve stabilization to ensure that structures, systems and components are in place to reliably maintain stable conditions for the long term until their functions are no longer needed. Post-accident preparations for decommissioning take decades. Arrangements are necessary to maintain the necessary expertise and workforce throughout this entire period.

Decision making on interim decommissioning stages and on the final conditions of the site and the damaged reactors needs to include a dialogue with stakeholders. Decision making on decommissioning depends on the conditions of the damaged reactors, fuel and debris, which cannot be determined in the period immediately following an accident. Factors to be considered in decision making include: dose levels for workers in decommissioning; the volumes and types of waste generated; and the efforts necessary for waste treatment. In the early stage of cleanup activities, it is unrealistic to predict the final conditions of the plant site, but expectations and plans for the land need to be considered in the decision making process.

— **Retrieving damaged fuel and characterizing and removing fuel debris require solutions that are specific to the accident, and special methods and tools may need to be developed.**

A reactor accident involving damage to nuclear fuel results in particular conditions in the reactor that are unique to the accident. The removal and management of damaged fuel elements and of debris from melted fuel are complex tasks. The debris needs to be characterized, removed, packaged and placed in storage until disposal is implemented, under difficult conditions, associated largely with high radiation levels.

— **National strategies and measures for post-accident recovery need to include the development of a generic strategy for managing contaminated liquid and solid material and radioactive waste, supported by generic safety assessments for discharge, storage and disposal.**

  A waste management strategy is needed for the implementation of pre-disposal management (e.g. handling, treatment, conditioning and storage) of accident-generated contaminated material and radioactive waste. It also needs to identify appropriate routes for the disposal of materials. Waste management strategies may involve the use of existing processing, storage and disposal facilities, such as incinerators or leachate controlled landfills. However, other approaches may be necessary, depending on the volumes and characteristics of the waste involved. The development of such strategies could be supported by the development of a generic safety case.

  Strategies for the post-accident management of large volumes of contaminated water are also necessary, including consideration of its controlled discharge to the environment. Although there is international guidance for discharges during the normal operation of nuclear facilities, further guidance on its application in post-accident situations is needed.

— **It is necessary to recognize the socioeconomic consequences of any nuclear accident and of the subsequent protective actions, and to develop revitalization and reconstruction projects that address issues such as reconstruction of infrastructure, community revitalization and compensation.**

  Nuclear accidents and the protective and remedial actions introduced in both the emergency phase and the post-accident recovery phase, with the objective of reducing doses, have far-reaching consequences on the way of life of the affected population. Engagement of stakeholders at various stages of remediation and recovery is essential.

— **Support by stakeholders is essential for all aspects of post-accident recovery. In particular, engagement of the affected population in the decision making processes is necessary for the success, acceptability and effectiveness of the recovery and for the revitalization of communities. An effective recovery programme requires the trust and the involvement of the affected population. Confidence in the implementation of recovery measures has to be built through processes of dialogue, the provision of consistent, clear and timely information, and support to the affected population.**

  Governments need to provide a realistic description of a recovery programme to the public that is consistent, clear and timely. A variety of information channels, including social media, need to be used to reach all interested groups.

  Perceptions of radiation risks and answers to questions about ‘safe’ radiation levels have many dimensions, including scientific, societal and ethical. These answers need to be clearly communicated to relevant communities through educational programmes — ideally before an accident has occurred.

  It is important that the affected population receive support for local recovery efforts. Support for self-help actions related to remediation and for rebuilding businesses can increase involvement in the recovery programme, and build the trust of the affected population.

6. THE IAEA RESPONSE TO THE ACCIDENT

This section provides an overview of key IAEA activities following the Fukushima Daiichi accident, both in the immediate phase and in the longer term. These include initial activities, IAEA missions to Japan, the Ministerial Conferences on Nuclear Safety and the IAEA Action Plan.

The IAEA is the depositary for the Convention on Nuclear Safety, and its role is to provide the Secretariat for the meetings by convening, preparing and servicing these meetings, as well as transmitting relevant information to the Contracting Parties. The activities related to the meetings of the Contracting Parties to the Convention on Nuclear Safety following the Fukushima Daiichi accident are also presented in this section.

6.1. IAEA ACTIVITIES

6.1.1. Initial activities

The responsibility for responding to a nuclear or radiological emergency and for the protection of workers, the public and the environment, rests with the operating organization at the level of the facility concerned, and with the affected State at the local, regional and national levels.

The IAEA has a central role in the international framework[115] for emergency preparedness and response. This role includes: (1) notification and official information exchange through officially designated contact points; (2) provision of timely, clear and understandable information; (3) provision and facilitation of international assistance upon request; and (4) coordination of the inter-agency response.[116]

The IAEA discharges this role through its Incident and Emergency System (IES). This system includes a 24-hour contact point and an operational focal point, the Incident and Emergency Centre (IEC).

At 06:42 UTC[117] on 11 March 2011, the IAEA activated the IES following a notification from the IAEA's International Seismic Safety Centre. This notification indicated the occurrence of an earthquake, the potential for damage at four NPPs[118] on the north-eastern coast of Japan and the risk of a tsunami [143]. At 07:21 UTC, the IAEA established initial communication with the official contact point designated by Japan under the Early Notification Convention and the Assistance Convention.

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[115] The international emergency preparedness and response framework at the time of the accident consisted of: (a) international legal instruments and agreements, in particular the Convention on Early Notification of a Nuclear Accident (Early Notification Convention) and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (Assistance Convention); (b) IAEA safety standards and technical guidance in the area of emergency preparedness and response; and (c) international operational arrangements and tools, in particular the Emergency Notification and Assistance Technical Operations Manual (ENATOM), the IAEA Response and Assistance Network (RANET), and the Joint Radiation Emergency Management Plan of the International Organizations (JPLAN).

[116] The primary coordinating body for nuclear and radiological emergencies is the Inter-Agency Committee on Radiological and Nuclear Emergencies (IACRNE). This body was established following the Chernobyl accident in 1986 and currently includes 18 international organizations. One of the primary roles of IACRNE is the development and maintenance of the Joint Radiation Emergency Management Plan of the International Organizations (JPLAN 2010 at the time of the accident).

[117] Universal Time Coordinated (UTC) is nine hours behind Japan Standard Time.

[118] Fukushima Daiichi and Fukushima Daini of the Tokyo Electric Power Company (TEPCO), Onagawa (Tohoku Power Company) and Tokai (Japan Atomic Power Company).

In the initial days of the accident, it became evident that the reactors and the fuel in the spent fuel pools at the Fukushima Daiichi NPP could be at risk of severe damage. Consequently, the IAEA established teams to evaluate key nuclear and radiological safety issues. The IAEA Laboratories[119] reviewed environmental data provided by the Japanese authorities on monitoring of the marine environment and received terrestrial environment samples for independent analysis.

The IAEA Director General visited Tokyo from 17 to 19 March for high level consultations, to express the solidarity of the international community and its full support to Japan in dealing with the consequences of the earthquake, tsunami and nuclear accident, and to convey offers of assistance from more than a dozen countries. The Director General also discussed the possibility of the IAEA providing or coordinating specific types of assistance, such as expert missions and fact finding missions, and emphasized the importance of transparency and the timely provision of official information by Japan.

On 28 March, at a special briefing on the accident for IAEA Member States, the Director General announced that a high level IAEA Conference on Nuclear Safety would take place in Vienna before the summer. He stated that it was "vitally important that we learn the right lessons from what happened on 11 March and afterwards, in order to strengthen nuclear safety throughout the world" [315].

Between 18 March and 18 April, at the request of Japan, the IAEA sent four radiological monitoring teams to Japan to help validate the results of the more extensive measurements taken by the Japanese authorities. The teams undertook measurements at a number of locations inside and outside the 20 km evacuation zone around the Fukushima Daiichi NPP and in the vicinity of Tokyo. A senior IAEA official was sent to Japan to coordinate the relevant IAEA activities and to transmit offers of assistance from Member States to the Japanese authorities. IAEA liaison officers were sent to Tokyo to facilitate and improve communication with Japan's regulatory body, which at that time was NISA.

A joint Food Safety Assessment Team from the IAEA and FAO visited Japan from 26 to 31 March. The team provided advice and assistance to the authorities at the national and local levels on technical issues relating to food safety and agricultural countermeasures. Advice was provided on sampling and analytical strategies and interpretation of monitoring data to ensure that reliable, continuous updates could be provided on the extent of food contamination in the affected areas. These data were used for the development of mitigation and remediation strategies by the Japanese authorities.

An IAEA team of experts on boiling water reactors was sent to Japan on 3 April, concluding its work on 12 April. The team toured both the Fukushima Daiichi and Fukushima Daini sites, meeting plant personnel in order to better understand the accident, the mitigation actions taken up to that time and the basis of the major decisions that had been made. They also held meetings with staff of several government offices and had detailed technical discussions with TEPCO and NISA in Tokyo.

The first statement by the IAEA on the accident was made public less than three hours after the earthquake on 11 March. Five additional statements were published later that day, conveying information received from Japan. More than 120 updates were published up to 22 April 2011. The IAEA held 16 news conferences between 14 March and 2 June 2011, in addition to those held during the Director General's visit to Japan. The IAEA's public information activities also included responding to thousands of telephone calls and providing detailed technical responses to hundreds of queries from the media.

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[119] The IAEA Laboratories, located in Seibersdorf, Austria, and in Monaco, specialize in evaluating terrestrial and marine environmental samples, respectively.

The IAEA posted daily briefings for Member States and the public on its public web site. These briefings covered: the status of Units 1–6 at the Fukushima Daiichi NPP; radiation monitoring data for radionuclides such as ^{131}I, ^{134}Cs and ^{137}Cs; the results of radiation monitoring of food and information on restrictions on the distribution and consumption of food and drinking water; and data on monitoring of the marine environment. The IAEA also provided briefings on the accident to the Permanent Missions of IAEA Member States in Vienna.

6.1.2. IAEA missions to Japan

Based upon an agreement with the Government of Japan, an International Fact Finding Expert Mission was undertaken by experts from the IAEA and Member States from 24 May to 2 June 2011. The mission gathered information for a preliminary assessment of the accident at the Fukushima Daiichi NPP and on events at other sites (Fukushima Daini and Tokai Daini). In addition, generic safety issues associated with natural events were identified that needed further exploration or assessment on the basis of the IAEA safety standards.

The scope of the mission included: external events of natural origin; plant safety assessment and the application of defence in depth; plant response after an earthquake and tsunami; management of a severe accident; management of spent fuel in a severely degraded facility; emergency preparedness and response; and radiological consequences. The mission findings [34] included 15 conclusions and 16 lessons, which were reported to the IAEA Ministerial Conference on Nuclear Safety in June 2011.

Other IAEA missions to Japan are summarized in Table 6.1.

Following the recommendation of the second decommissioning mission, projects were started to enhance transparency and to provide independent assessments of monitoring of the marine environment by Japan. Proficiency tests were conducted at the IAEA Environment Laboratories in Monaco to monitor the performance and analytical capabilities of participating laboratories. The results of the marine monitoring programme are regularly updated on the IAEA's web site.

6.1.3. IAEA Ministerial Conference on Nuclear Safety

In June 2011, a Ministerial Conference on Nuclear Safety was convened by the Director General at IAEA Headquarters with the objective of strengthening nuclear safety by drawing on the lessons from the accident. The conference provided an opportunity to undertake, at the ministerial and senior technical levels, a preliminary assessment of the accident. The conference also considered actions for safety improvements, issues regarding emergency preparedness and response, and implications for the global nuclear safety framework.

The outcome was a Ministerial Declaration on Nuclear Safety [320], which outlined a number of measures to further improve nuclear safety, emergency preparedness and radiation protection of people and the environment worldwide. It also expressed the firm commitment of IAEA Member States to ensure that these measures were taken. The key measures were: to strengthen the IAEA safety standards; to systematically review the safety of all NPPs, including by expanding the IAEA's programme of expert peer reviews; to enhance the effectiveness of national nuclear regulatory bodies and ensure their independence; to strengthen the global emergency preparedness and response system; and to expand the IAEA's role in receiving and disseminating information. The Ministerial Declaration also requested the Director General to prepare a draft IAEA Action Plan on Nuclear Safety in consultation with Member States.

TABLE 6.1. IAEA MISSIONS TO JAPAN

Date	Mission	Objectives
7–15 Oct. 2011	International Mission on Remediation of Large Contaminated Areas Off-site the Fukushima Daiichi NPP [316]	Assist Japan's plans to remediate large areas contaminated by the accident. Review Japan's ongoing remediation strategies, plans and activities, including contamination mapping. Share findings with the international community to disseminate lessons from the accident.
23–31 Jan. 2012	IAEA Mission to Review NISA's Approach to Comprehensive Assessments for Safety of Existing Power Reactor Facilities [317]	Review (at the request of the Japanese Government) NISA's Comprehensive Assessments for the Safety of Existing Power Reactor Facilities, and the results of the licensee's assessments.
30 Jul.–11 Aug. 2012	IAEA Mission to Onagawa Nuclear Power Station to Examine the Performance of Systems, Structures and Components Following the Great East Japanese Earthquake and Tsunami [318]	Examine the performance of structures, systems and components following the earthquake and tsunami.
15–22 Apr. 2013	International Peer Review of the Mid-and-Long-Term Roadmap Towards the Decommissioning of TEPCO's Fukushima Daiichi NPP Units 1–4 (first mission) [319]	Review the 'Decommissioning Roadmap'; challenges; condition of the reactors; management of waste; protection of employees; and structural integrity of reactor buildings and other structures.
14–21 Oct. 2013	Follow-up International Mission on Remediation of Large Contaminated Areas Off-site the Fukushima Daiichi NPP [265]	Evaluate the progress of ongoing remediation work in Japan and provide advice on addressing remediation challenges.
6–12 Nov. 2013	Expert visit on marine monitoring	Observe seawater sampling and data analysis in Fukushima (7 and 8 Nov. 2013) and meet the relevant Japanese authorities in Tokyo to collect information on marine monitoring conducted by Japan under its Sea Area Monitoring Plan.
25 Nov.– 4 Dec. 2013	International Peer Review of the Mid- and Long-Term Roadmap Towards the Decommissioning of TEPCO's Fukushima Daiichi NPP Units 1–4 (second mission) [288]	Review the updated 'Decommissioning Roadmap'; removal of spent fuel from storage pools; management of contaminated water; waste management; and marine monitoring.
10–16 Sept. and 4–14 Nov. 2014	Expert mission on marine monitoring confidence building and data quality assurance	Focus on availability of marine monitoring results.
8–15 Feb. 2015	International Peer Review of the Mid-and-Long-Term Roadmap Towards the Decommissioning of TEPCO's Fukushima Daiichi NPP Units 1–4 (third mission) [289]	Review implementation of the Decommissioning Roadmap'; management of contaminated water; groundwater ingress; removal of spent fuel and fuel debris; and institutional and organisational issues.

6.1.4. The IAEA Action Plan on Nuclear Safety

The draft IAEA Action Plan on Nuclear Safety was approved by the Board of Governors in September 2011. The Action Plan was then presented at the regular session of the 2011 IAEA General Conference, where it was unanimously endorsed by Member States [144]. The General Conference subsequently called upon the IAEA Secretariat and Member States to implement the actions as an overarching priority in a comprehensive and coordinated manner [321].

Activities under the Action Plan started immediately after its adoption. The full and effective implementation of the activities in this plan required joint efforts and full commitment by the IAEA Secretariat, Member States and other stakeholders.

Since the adoption of the Action Plan, significant progress has been made in several key areas, such as: assessments of the safety vulnerabilities of NPPs; strengthening of the IAEA's peer review services; review and revision, as necessary, of the relevant IAEA safety standards; improvements in emergency preparedness and response capabilities; capacity building; and enhancing communication and information sharing with Member States, international organizations and the public. Regular progress reports were presented to the IAEA Board of Governors and the IAEA General Conference [322–324].

In the resolution adopting the Action Plan, the IAEA's role in responding to a nuclear emergency was expanded to include providing Member States, international organizations and the general public with timely, clear, factually correct, objective and easily understandable information on its potential consequences. This is to include an analysis of available information and a prognosis of possible scenarios based on the evidence, scientific knowledge and the capabilities of Member States.

A number of international experts meetings (IEMs) were organized in different areas of safety to analyse the technical aspects and to learn the lessons from the Fukushima Daiichi accident. Reports on these key safety areas, including the results of the IEMs, were published by the IAEA (see Table 6.2).

Additional reports were prepared in 2013 on the following subjects:

— Preparedness and Response for a Nuclear or Radiological Emergency in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, based on a series of technical meetings held in 2012–2013 [327].
— Strengthening Regulatory Effectiveness in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, based on the results of the International Conference on Effective Nuclear Regulatory Systems, Ottawa, Canada, 2013 [328].

6.1.5. Cooperation with Fukushima Prefecture

A memorandum of cooperation between the IAEA and Fukushima Prefecture was signed in December 2012 [329]. On the basis of this memorandum, practical arrangements on cooperation in the areas of radiation monitoring and remediation [330], human health [331], and emergency preparedness and response [332] were signed, with Fukushima Prefecture, the Fukushima Medical University and the Ministry of Foreign Affairs of Japan, respectively.

An IAEA Response and Assistance Network (RANET) Capacity Building Centre was designated in Fukushima City in May 2013. The centre is used for a range of IAEA activities aimed at enhancing capacity for emergency preparedness and response, both in Japan and worldwide. A number of training workshops were held at the centre dealing with monitoring during a nuclear and radiological emergency, notification, reporting and requesting assistance, and emergency preparedness and response.

TABLE 6.2. INTERNATIONAL EXPERTS MEETINGS (IEMs)

Date	Title	Focus
19–22 Mar. 2012	IEM 1: Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant [42]	Analyse technical aspects; understand root causes; share lessons from the accident.
18–20 Jun. 2012	IEM 2: Enhancing Transparency and Communication Effectiveness in the Event of a Nuclear or Radiological Emergency [314]	Identify and analyse lessons from the accident and discuss best practices for improving the dissemination of information.
4–7 Sep. 2012	IEM 3: Protection against Extreme Earthquakes and Tsunamis in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant [325]	Share lessons; exchange information and identify issues to be further investigated on: seismic and tsunami hazard assessment; special flooding issues; uncertainties associated with hazard assessments; approaches to establishing design values; addressing beyond design basis events; safety against earthquakes and tsunamis.
28 Jan.–1 Feb. 2013	IEM 4: Decommissioning and Remediation after a Nuclear Accident [293]	Examine short term and long term issues for decommissioning of accident damaged facilities; management of radioactive waste arising from a nuclear accident; and remediation of the off-site environment.
21–24 May 2013	IEM 5: Human and Organizational Factors in Nuclear Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant [67]	Explore ways to improve nuclear safety culture across a range of key institutions, including operating organizations and regulatory bodies.
17–21 Feb. 2014	IEM 6: Radiation Protection after the Fukushima Daiichi Accident: Promoting Confidence and Understanding [326]	Focus on radiation protection issues highlighted by the Fukushima Daiichi accident and how these could be addressed at both the national and international levels.
17–20 Mar. 2014	IEM 7: Severe Accident Management in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant	Gather and share knowledge and experience gained in the light of the Fukushima Daiichi accident concerning severe accident management; identify lessons and best practices.
16–20 Feb. 2015	IEM 8: Strengthening Research and Development Effectiveness in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant	Facilitate the exchange of information arising from new R&D activities undertaken by IAEA Member States, as well as by the OECD Nuclear Energy Agency (OECD/NEA) and other international organizations dealing with severe accidents at NPPs, including those affecting spent fuel pools; further strengthen international collaboration among Member States and international organizations.
20–24 Apr. 2015	IEM 9: Assessment and Prognosis in Response to a Nuclear or Radiological Emergency	Facilitate the exchange of timely, clear, factually correct information during a nuclear or radiological emergency and its potential consequences, including analysis of available information and prognosis of possible scenarios based on the evidence, scientific knowledge and the capabilities of Member States.

6.1.6. Fukushima Ministerial Conference on Nuclear Safety

In December 2012, the Government of Japan organized a Ministerial Conference in Fukushima Prefecture, co-sponsored by the IAEA, with the principal objective of contributing to strengthening nuclear safety worldwide [333]. The conference provided an opportunity to share with the international community further knowledge and lessons learned from the accident and to discuss the progress of international efforts aimed at strengthening nuclear safety, including progress in the implementation of the Action Plan.

Discussions included: levels of radiation at Fukushima Daiichi; post-accident challenges for decommissioning and remediation; and the status of damage and recovery in the areas around the plant. The conference highlighted the importance of taking actions on the basis of scientific and factual information in the event of a nuclear or radiological emergency, and of enhancing international cooperation.

6.2. MEETINGS OF THE CONTRACTING PARTIES TO THE CONVENTION ON NUCLEAR SAFETY

Box 6.1. The Convention on Nuclear Safety

The Convention on Nuclear Safety was adopted in Vienna on 17 June 1994 [334]. It is the first legally binding international treaty to address the safety of nuclear installations (land based civil NPPs) and aims: to achieve and maintain a high level of nuclear safety worldwide; to establish and maintain effective defences against potential radiological hazards to protect individuals, society and the environment; and to prevent accidents with radiological consequences and to mitigate such consequences should they occur. The Convention entered into force on 24 October 1996. As of March 2015, there were 77 Contracting Parties.

The obligations of the Contracting Parties are based to a large extent on the principles now contained in the IAEA Fundamental Safety Principles (SF-1) [335]. These obligations cover, in particular: the siting, design, construction and operation of nuclear installations; the establishment and maintenance of a legislative and regulatory framework; the establishment of a regulatory body with adequate authority, competence, and financial and human resources; the availability of adequate financial and human resources to support the safety of nuclear installations; the assessment and verification of safety; quality assurance; and emergency preparedness.

Contracting Parties are required to submit a report on the measures they have taken to implement each of the obligations of the Convention. These reports are reviewed during review meetings of the Contracting Parties held every three years under the auspices of the IAEA.

6.2.1. Extraordinary Meeting of the Contracting Parties to the Convention on Nuclear Safety

At the Fifth Review Meeting of the Contracting Parties to the Convention on Nuclear Safety, held from 4 to 14 April 2011, the Parties adopted a statement in which they, inter alia, reaffirmed their commitment to the objectives of the Convention. The Contracting Parties agreed to hold an extraordinary meeting to review and discuss initial analyses of the accident and the effectiveness of the Convention.

The Extraordinary Meeting was convened at IAEA Headquarters in Vienna from 27 to 31 August 2012. The Contracting Parties discussed: external events; design issues; severe accident management and recovery (on-site); national organizations; emergency preparedness and response; post-accident management (off-site); and international cooperation.

The Contracting Parties also agreed by consensus on a number of concrete actions to enhance the effectiveness of the peer review process. The three underlying guidance documents[120] of the Convention were amended in order to enhance the transparency of the review process, encourage Contracting Parties to refer to the IAEA safety standards in their National Reports, and reinforce efforts for continuous improvement by performing periodic reassessments of safety through periodic safety reviews or alternative methods.

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[120] The Rules of Procedure and Financial Rules [336], the Guidelines regarding the Review Process [337] and the Guidelines regarding the National Reports [338].

A Working Group on Effectiveness and Transparency was established to report to the Sixth Review Meeting of the Contracting Parties on further actions to strengthen the Convention on Nuclear Safety and on proposals to amend it, where necessary. The Contracting Parties also considered a list of action oriented objectives for strengthening nuclear safety, which was attached to the Summary Report of the Extraordinary Meeting [339].

6.2.2. Sixth Review Meeting of the Contracting Parties to the Convention on Nuclear Safety

The Sixth Review Meeting of the Contracting Parties to the Convention on Nuclear Safety was held from 24 March to 4 April 2014. During a special session of the meeting, Contracting Parties reported on the actions carried out in light of the Fukushima Daiichi accident. It was noted that, while nuclear safety and arrangements for emergency preparedness and response had improved, more remained to be done. National safety frameworks were being further enhanced, with steps taken to establish the effective independence of regulatory bodies and to update regulations. International cooperation had also increased, with greater participation in peer reviews and exchange of information [340].

Contracting Parties to the Convention on Nuclear Safety reported on the implementation of safety upgrades, including: the introduction of additional means to withstand prolonged loss of power and cooling; enhancement of power systems to improve reliability; re-evaluation of site-specific external natural hazards and multi-unit events; improvements of on-site and off-site emergency control centres to ensure protection from extreme external events and radiation hazards; the strengthening of measures to preserve containment integrity; and improvement of severe accident management provisions and guidelines.

The Contracting Parties also adopted proposals to further amend the underlying guidance documents of the Convention and made recommendations for action by the IAEA Secretariat, the Contracting Parties and other organizations.

Finally, the Contracting Parties decided by vote to convene a Diplomatic Conference within one year to consider a proposal by Switzerland to amend Article 18 of the Convention, on the design and construction of both new and existing NPPs.

6.2.3. Diplomatic Conference and the Vienna Declaration on Nuclear Safety

The Diplomatic Conference was convened by the Director General at IAEA Headquarters on 9 February 2015 and was attended by 71 Contracting Parties. The Parties unanimously adopted the Vienna Declaration on Nuclear Safety. This Declaration included the following principles for the implementation of the third objective of the Convention, which is to prevent accidents with radiological consequences and to mitigate such consequences should they occur:

> "1. New nuclear power plants are to be designed, sited, and constructed, consistent with the objective of preventing accidents in the commissioning and operation and, should an accident occur, mitigating possible releases of radionuclides causing long-term off site contamination and avoiding early radioactive releases or radioactive releases large enough to require long-term protective measures and actions.
>
> 2. Comprehensive and systematic safety assessments are to be carried out periodically and regularly for existing installations throughout their lifetime in order to identify safety improvements that are oriented to meet the above objective. Reasonably practicable or achievable safety improvements are to be implemented in a timely manner.
>
> 3. National requirements and regulations for addressing this objective throughout the lifetime of nuclear power plants are to take into account the relevant IAEA safety standards and, as

appropriate, other good practices as identified *inter alia* in the Review Meetings of the CNS [Convention on Nuclear Safety]” [341].

The Vienna Declaration took into account the significant number of efforts and initiatives at the international, national and regional levels that had taken place since the accident at the Fukushima Daiichi NPP to enhance nuclear safety worldwide.

REFERENCES

[1] NATIONAL POLICE AGENCY, Damage Situation and Police Countermeasures Associated with the 2011Tohoku District–off the Pacific Ocean Earthquake (2015), https://www.npa.go.jp/archive/keibi/biki/higaijokyo_e.pdf

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Introductory Statement to Board of Governors (2013), https://www.iaea.org/newscenter/statements/introductory-statement-board-governors-3

[3] GOVERNMENT OF JAPAN, NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Report of the Japanese Government to the IAEA Ministerial Conference on Nuclear Safety: The Accident at TEPCO's Fukushima Nuclear Power Stations (2011), http://www.iaea.org/newscenter/focus/fukushima/japan-report

[4] GOVERNMENT OF JAPAN, NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Additional Report of the Japanese Government to the IAEA: The Accident at TEPCO's Fukushima Nuclear Power Stations, Second Report (2011), http://www.meti.go.jp/english/earthquake/nuclear/iaea/iaea_110911.html

[5] INVESTIGATION COMMITTEE ON THE ACCIDENT AT THE FUKUSHIMA NUCLEAR POWER STATIONS OF TOKYO ELECTRIC POWER COMPANY, Final Report, Cabinet Secretariat of the Government of Japan (2012), http://www.cas.go.jp/jp/seisaku/icanps/eng/final-report.html

[6] INVESTIGATION COMMITTEE ON THE ACCIDENT AT THE FUKUSHIMA NUCLEAR POWER STATIONS OF TOKYO ELECTRIC POWER COMPANY, Interim Report, Cabinet Secretariat of the Government of Japan (2011), http://www.cas.go.jp/jp/seisaku/icanps/eng/interim-report.html

[7] NATIONAL DIET OF JAPAN FUKUSHIMA NUCLEAR ACCIDENT INDEPENDENT INVESTIGATION COMMISSION, The Official Report of the Fukushima Nuclear Accident Independent Investigation Commission, National Diet of Japan, Tokyo (2012).

[8] TOKYO ELECTRIC POWER COMPANY, Fukushima Nuclear Accident Analysis Report, TEPCO, Tokyo (2012).

[9] TOKYO ELECTRIC POWER COMPANY, Evaluation of the Situation of Cores and Containment Vessels of Fukushima Daiichi Nuclear Power Station Units-1 to 3 and Examination into Unsolved Issues in the Accident Progression, TEPCO, Tokyo (2013).

[10] TOKYO ELECTRIC POWER COMPANY, Report on the Investigation and Study of Unconfirmed/Unclear Matters in the Fukushima Nuclear Accident, Progress Rep. No. 2, TEPCO, Tokyo (2014).

[11] NUCLEAR REGULATION AUTHORITY, Analysis of the TEPCO Fukushima Daiichi NPS Accident, Interim Rep. (2014), https://www.iaea.org/sites/default/files/anaylysis_nra1014.pdf

[12] JAPAN METEOROLOGICAL AGENCY, Information on the 2011 off the Pacific Coast of Tohoku Earthquake (2015), http://www.jma.go.jp/jma/en/2011_Earthquake/Information_on_2011_Earthquake.html

[13] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Power Reactor Information System (PRIS) (2015), http://www.iaea.org/pris/

[14] JAPAN METEOROLOGICAL AGENCY, Tsunami Information (Estimated Tsunami Arrival Time and Height) (2011), http://www.jma.go.jp/en/tsunami/info_04_20110311145026.html

[15] COASTAL ENGINEERING COMMITTEE OF JAPAN SOCIETY OF CIVIL ENGINEERS, The 2011 off the Pacific Coast of Tohoku Earthquake Tsunami Information (2013), http://www.coastal.jp/tsunami2011/index.php?Field%20survey%20results

[16] NUCLEAR AND INDUSTRIAL SAFETY AGENCY, Fukushima Daiichi Unit 1 Establishment Permit, NISA (1966) (in Japanese).

[17] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Dry Storage Cask Leak Test Results Reported to METI (2013) (in Japanese),
http://www.meti.go.jp/earthquake/nuclear/20130530_03.html
[18] TOKYO ELECTRIC POWER COMPANY, Operation Manuals of TEPCO Fukushima Daiichi NPP in Case of Accident (2011) (in Japanese),
http://www.nsr.go.jp/archive/nisa/earthquake/manual/manual_index.html
[19] Act on Special Measures Concerning Nuclear Emergency Preparedness, Act No. 156 of 1999, as last amended by Act No. 118 of 2006 (Japan),
http://www.cas.go.jp/jp/seisaku/hourei/data/ASMCNEP.pdf
[20] TOKYO ELECTRIC POWER COMPANY, Building diagrams for 1F ground level and cross section of Unit 4 and the common spent fuel pool, official communication (2014).
[21] Order for Enforcement of the Act on Special Measures Concerning Nuclear Emergency Preparedness No. 195 of April 5, 2000 (Japan) (in Japanese),
http://law.e-gov.go.jp/htmldata/H12/H12SE195.html
[22] NUCLEAR SAFETY COMMISSION, Accident Management: Measures against Severe Accidents at Light Water Nuclear Power Reactor Facilities (1992) (in Japanese),
http://www.mext.go.jp/b_menu/hakusho/nc/t19920528001/t19920528001.html
[23] NUCLEAR SAFETY COMMISSION, Accident Management for Severe Accidents at Light Water Power Reactor Installations, NSCRG: L-AM-II.01, NSC, Tokyo (1997).
[24] TOKYO ELECTRIC POWER COMPANY, Roadmap towards Restoration from the Accident at Fukushima Daiichi Nuclear Power Station (2011),
http://www.meti.go.jp/english/speeches/pdf/20110417_a.pdf
[25] INTERNATIONAL ATOMIC ENERGY AGENCY, WORLD METEOROLOGICAL ORGANIZATION, Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. SSG-18, IAEA, Vienna (2011).
[26] INTERNATIONAL ATOMIC ENERGY AGENCY, Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. NS-R-3, IAEA, Vienna (2003).
[27] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Power Plants: Design, IAEA Safety Standards Series No. NS-R-1, IAEA, Vienna (2000). (This publication is superseded by SSR-2/1 (2012)).
[28] INTERNATIONAL ATOMIC ENERGY AGENCY, Earthquakes and Associated Topics in Relation to Nuclear Power Plant Siting, Safety Series No. 50-SG-S1, IAEA, Vienna (1979). (This publication is superseded by SSG-9 (2010)).
[29] Nuclear Reactor Establishment Change Permit Application, Nuclear Industry Report to the Government No. 5–11 (1993).
[30] SAKAI, T., TOKYO ELECTRIC POWER COMPANY, “Past tsunami assessments and tsunami on 11 March 2011”, paper presented at 5th Meeting of Working Group 2, Vienna, 2014.
[31] JAPAN SOCIETY OF CIVIL ENGINEERS, Tsunami Assessment Method for Nuclear Power Plants in Japan (2002) (in Japanese),
http://committees.jsce.or.jp/ceofnp/node/5
[32] NUCLEAR SAFETY COMMISSION, Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities, NSC, Tokyo (2006).
[33] HEADQUARTERS FOR EARTHQUAKE RESEARCH PROMOTION, On the Long-term Evaluation of Seismic Activity off Eastern Japan between the Sanriku Coast and the Boso Peninsula (2002) (in Japanese),
http://www.jishin.go.jp/main/chousa/kaikou_pdf/sanriku_boso.pdf
[34] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA International Fact Finding Expert Mission of the Fukushima Dai-ichi NPP Accident Following the Great East Japan Earthquake and Tsunami (2011),
http://www-pub.iaea.org/MTCD/meetings/PDFplus/2011/cn200/documentation/cn200_Final-Fukushima-Mission_Report.pdf
[35] GOVERNMENT OF INDIA, Actions Taken for Indian NPPs Subsequent to Fukushima Nuclear Accident. National Report to the Convention on Nuclear Safety (2012),
http://www.aerb.gov.in/AERBPortal/pages/English/t/documents/CNS2012.pdf
[36] INTERNATIONAL ATOMIC ENERGY AGENCY, Extreme External Events in the Design and Assessment of Nuclear Power Plants, IAEA-TECDOC-1341, IAEA, Vienna (2003).

[37] INTERNATIONAL ATOMIC ENERGY AGENCY, International Reporting System for Operating Experience (2014) (unpublished).
[38] INTERNATIONAL ATOMIC ENERGY AGENCY, Follow-up IAEA Mission in Relation to the Findings and Lessons Learned from the 16 July 2007 Earthquake at Kashiwazaki-Kariwa NPP, IAEA, Vienna (2009).
[39] INTERNATIONAL NUCLEAR SAFETY ADVISORY GROUP, Defence in Depth in Nuclear Safety, INSAG-10, IAEA, Vienna (1996).
[40] INTERNATIONAL NUCLEAR SAFETY ADVISORY GROUP, Basic Safety Principles for Nuclear Power Plants: 75-INSAG-3 Rev. 1, INSAG-12, IAEA, Vienna (1999).
[41] INTERNATIONAL ATOMIC ENERGY AGENCY, Severe Accident Management Programmes for Nuclear Power Plants, IAEA Safety Standards Series No. NS-G-2.15, IAEA, Vienna (2009).
[42] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA, Vienna (2012).
[43] INTERNATIONAL ATOMIC ENERGY AGENCY, Topical Issues in Nuclear Installation Safety: Defence in Depth — Advances and Challenges for Nuclear Installation Safety, IAEA-TECDOC-CD-1749, IAEA, Vienna (2014).
[44] SANDIA NATIONAL LABORATORIES, Fukushima Daiichi Accident Study (Status as of April 2012) SAND2012-6173, SNL, Albuquerque, NM (2012).
[45] ELECTRIC POWER RESEARCH INSTITUTE, Fukushima Technical Evaluation, Phase 1 — MAAP5 Analysis, EPRI, Palo Alto (2013).
[46] TOKYO ELECTRIC POWER COMPANY, Report on the Investigation and Study of Unconfirmed/Unclear Matters in the Fukushima Nuclear Accident. Progress Rep. No. 2 (2014), http://www.tepco.co.jp/en/press/corp-com/release/betu14_e/images/140806e0101.pdf
[47] INTERNATIONAL ATOMIC ENERGY AGENCY, Development and Application of Level 1 Probabilistic Safety Assessment for Nuclear Power Plants, IAEA Safety Standards Series No. SSG-3, IAEA, Vienna (2010).
[48] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Safety Glossary: Terminology Used in Nuclear Safety and Radiation Protection: 2007 Edition, IAEA, Vienna (2007).
[49] INTERNATIONAL ATOMIC ENERGY AGENCY, Development and Application of Level 2 Probabilistic Safety Assessment for Nuclear Power Plants, IAEA Safety Standards Series No. SSG-4, IAEA, Vienna (2010).
[50] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Power Plants: Operation, IAEA Safety Standards Series No. NS-R-2, IAEA, Vienna (2000). (This publication is superseded by SSR-2/2 (2011)).
[51] INTERNATIONAL ATOMIC ENERGY AGENCY, Integrated Regulatory Review Service (IRRS) to Japan, IAEA-NSNI-IRRS-2007/01, IAEA, Vienna (2007).
[52] INTERNATIONAL ATOMIC ENERGY AGENCY, Periodic Safety Review of Nuclear Power Plants, IAEA Safety Standards Series No. NS-G-2.10, IAEA, Vienna (2003). (This publication is superseded by SSG-25 (2013)).
[53] INTERNATIONAL ATOMIC ENERGY AGENCY, Lessons Learned from the JCO Nuclear Criticality Accident in Japan in 1999 (2009), http://www-ns.iaea.org/downloads/iec/tokaimura-report.pdf
[54] SHIROYAMA, H., “Regulatory failures of nuclear safety in Japan — the case of Fukushima accident”, paper presented at Earth System Governance Tokyo Conf.: Complex Architectures, Multiple Agents, Tokyo (2013), http://tokyo2013.earthsystemgovernance.org/wp-content/uploads/2013/01/0202-SHIROYAMA_Hideaki-.pdf
[55] GOVERNMENT OF JAPAN, Convention on Nuclear Safety National Report of Japan for the Fifth Review Meeting (2010), http://www.nsr.go.jp/archive/nsc/NSCenglish/documents/conventions/2011.pdf
[56] KATO, S., “Recent development in safety regulation of nuclear fuel cycle activities”, Proc. Int. Conf. on Topical Issues in Nuclear Safety, Vienna, 2001, IAEA, Vienna (2002).
[57] INTERNATIONAL ATOMIC ENERGY AGENCY, Governmental, Legal and Regulatory Framework for Safety, IAEA Safety Standards Series No. GSR Part 1, IAEA, Vienna (2010).

[58] INTERNATIONAL ATOMIC ENERGY AGENCY, Periodic Safety Review of Nuclear Power Plants: Experience of Member States, IAEA-TECDOC-1643, IAEA, Vienna (2010).
[59] NUCLEAR REGULATION AUTHORITY, FY2012 Annual Report, NRA, Tokyo (2012).
[60] NUCLEAR REGULATION AUTHORITY, Enforcement of the New Regulatory Requirements for Commercial Nuclear Power Reactors (2013), http://www.nsr.go.jp/data/000067212.pdf
[61] INTERNATIONAL NUCLEAR SAFETY ADVISORY GROUP, Safety Culture, Safety Series No. 75-INSAG-4, IAEA, Vienna (1991).
[62] INTERNATIONAL ATOMIC ENERGY AGENCY, The Management System for Nuclear Installations, IAEA Safety Standards Series No. GS-G-3.5, IAEA, Vienna (2009).
[63] INTERNATIONAL ATOMIC ENERGY AGENCY, Developing Safety Culture in Nuclear Activities: Practical Suggestions to Assist Progress, Safety Reports Series No. 11, IAEA, Vienna (1998).
[64] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Culture in Nuclear Installations, IAEA-TECDOC-1329, IAEA, Vienna (2002).
[65] INSTITUTE OF NUCLEAR POWER OPERATIONS, Lessons Learned from the Nuclear Accident at the Fukushima Daiichi Nuclear Power Station, INPO 11-005 Addendum, INPO, Atlanta (2012).
[66] NUCLEAR REGULATORY COMMISSION, A Comparison of US and Japanese Regulatory Requirements in Effect at the Time of the Fukushima Accident, NRC, Washington, DC (2013).
[67] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Human and Organizational Factors in Nuclear Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA, Vienna (2014).
[68] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS OFFICE FOR THE COORDINATION OF HUMANITARIAN AFFAIRS, WORLD HEALTH ORGANIZATION, Arrangements for Preparedness for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GS-G-2.1, IAEA, Vienna (2007).
[69] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS OFFICE FOR THE COORDINATION OF HUMANITARIAN AFFAIRS, WORLD HEALTH ORGANIZATION, Preparedness and Response for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GS-R-2, IAEA, Vienna (2002).
[70] Disaster Countermeasures Basic Act, Act No. 223 of 15 November 1961, as last amended in 1997 (Japan), http://www.adrc.asia/documents/law/DisasterCountermeasuresBasicAct.pdf
[71] Ordinance for Enforcement of the Act on Special Measures Concerning Nuclear Emergency Preparedness No. 2 of April 5, 2000 (Japan) (in Japanese), http://law.e-gov.go.jp/haishi/H12F03103016002.html
[72] NUCLEAR REGULATION AUTHORITY, Comment received on Section 3.1 on Technical Volume 3, official communication (23 July 2014).
[73] GOVERNMENT OF JAPAN, Nuclear Emergency Response Manual, Government of Japan (2010) (in Japanese).
[74] FUKUSHIMA PREFECTURE, Fukushima Prefecture Disaster Management Plan (2009) (in Japanese).
[75] TOKYO ELECTRIC POWER COMPANY, Nuclear Operator Emergency Action Plan for the Fukushima Dai-ichi Nuclear Power Station, TEPCO, Tokyo (2010).
[76] TOKYO ELECTRIC POWER COMPANY, Specific Event Report, Fax No. 0042 (11 March 2011).
[77] TOKYO ELECTRIC POWER COMPANY, Report from Nuclear Power Plant Management of TEPCO to Minister of Economy, Trade and Industry, Fax No. 1560 (11 March 2011).
[78] GOVERNMENT OF JAPAN, CENTRAL DISASTER MANAGEMENT COUNCIL, The Basic Disaster Management Plan, Government of Japan, Tokyo (2008).
[79] GOVERNMENT OF JAPAN, Official web site of the Prime Minister of Japan and His Cabinet (2015), http://japan.kantei.go.jp/index.html
[80] NUCLEAR REGULATION AUTHORITY, About NISA (2015), http://www.nsr.go.jp/archive/nisa/english/aboutnisa/contact.html

[81] TOKYO ELECTRIC POWER COMPANY, TEPCO at a Glance (2015), http://www.tepco.co.jp/en/corpinfo/overview/p-glance-e.html
[82] NUCLEAR REGULATION AUTHORITY, About the Nuclear Safety Commission (2015), http://www.nsr.go.jp/archive/nsc/NSCenglish/aboutus/overview/overview.htm
[83] NUCLEAR REGULATION AUTHORITY, About JNES (2015), http://www.nsr.go.jp/archive/jnes/english/index.html
[84] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Home page of the Ministry of Education, Culture, Sports, Science and Technology (2015), http://www.mext.go.jp/english/
[85] MINISTRY OF HEALTH, LABOUR AND WELFARE, Home page of the Ministry of Health, Labour and Welfare (2015), http://www.mhlw.go.jp/english/
[86] MINISTRY OF AGRICULTURE, FORESTRY AND FISHERIES, Home page of the Ministry of Agriculture, Forestry and Fisheries (2015), http://www.maff.go.jp/e/
[87] MINISTRY OF THE ENVIRONMENT, Home page of the Ministry of Environment (2015), http://www.env.go.jp/en/
[88] MINISTRY OF DEFENSE, Home page of the Ministry of Defense of Japan (2015), http://www.mod.go.jp/e/index.html
[89] JAPAN METEOROLOGICAL AGENCY, Home page of the Japan Meteorological Agency (2015), http://www.jma.go.jp/jma/indexe.html
[90] JAPAN ATOMIC ENERGY AGENCY, Home page of the Japan Atomic Energy Agency (2015), http://www.jaea.go.jp/english/index.html
[91] NATIONAL INSTITUTE OF RADIOLOGICAL SCIENCES, Home page of National Institute of Radiological Sciences (2015), http://www.nirs.go.jp/ENG/index.shtml
[92] JAPAN NUCLEAR ENERGY SAFETY ORGANIZATION, Initial Operations in the Local Nuclear Emergency Response Headquarters (2013), https://www.nsr.go.jp/archive/jnes/content/000124530.pdf
[93] NUCLEAR SAFETY COMMISSION, Regulatory Guide: Emergency Preparedness for Nuclear Facilities, NSC, Tokyo (1980).
[94] Ordinance on Prevention of Ionizing Radiation Hazards, Ordinance of the Ministry of Labour No. 41 of September 30, 1972, as last amended by Ordinance No. 172 of July 16, 2001 (Japan) (in Japanese), http://law.e-gov.go.jp/htmldata/S47/S47F04101000041.html
[95] MINISTRY OF HEALTH, LABOUR AND WELFARE, Enforcement of the Ministerial Ordinance on Exemption of the Ordinance on Prevention of Ionizing Radiation Hazards in Response to the Situation Resulting from the Tohoku–Pacific Ocean Earthquake in 2011 (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/rp/ri_0315_07.html
[96] MINISTRY OF HEALTH, LABOUR AND WELFARE, Consultation with and Recommendation from the Labor Policy Council on “the Outline of the Draft Ministerial Ordinance for Abolishment of Exemption in the Ordinance on Prevention of Ionizing Radiation Hazards in Response to the Situation Resulting from the Tohoku–Pacific Ocean Earthquake in 2011” (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/rp/pr_111121.html
[97] MINISTRY OF HEALTH, LABOUR AND WELFARE, Response and Action Taken by the MHLW of Japan on Radiation Protection for Workers Involved in the TEPCO Fukushima Daiichi NPP Accident, MHLW, Tokyo (2013).
[98] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Progress of the “Roadmap for Immediate Actions for the Assistance of Residents Affected by the Nuclear Incident" (2011). http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/110719_assistance_03.pdf
[99] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Progress of the “Roadmap for Immediate Actions for the Assistance of Residents Affected by the Nuclear Incident” (2011). http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/110617roadmap_assistance_report.pdf
[100] TOKYO ELECTRIC POWER COMPANY, Status of Improvement on Working Environment of workers in Fukushima Daiichi Nuclear Power Station (Attachment 2: About Cool Vest) (2011), http://www.tepco.co.jp/en/press/corp-com/release/11061013-e.html

[101] TOKYO ELECTRIC POWER COMPANY, Progress Status of Cooling (Reactors) (2011), http://www.tepco.co.jp/en/press/corp-com/release/betu11_e/images/110517e5.pdf
[102] MINISTRY OF HEALTH, LABOUR AND WELFARE, Occupational Safety and Health Department Notification (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/dr/dr/ri_0909_01.html
[103] MINISTRY OF HEALTH, LABOUR AND WELFARE, Guidelines on Prevention of Radiation Hazards for Workers Engaged in Decontamination Works (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/dr/dr/pr_120615_a03.pdf
[104] NUCLEAR REGULATION AUTHORITY, WG3 question 4, 1st submission, official communication (2013).
[105] GOVERNMENT OF JAPAN, WG3 question 5, 6th submission, official communication (2014).
[106] WATANABE, Y., "Relief activities conducted by the Japanese Red Cross Society after the Fukushima Daiichi Nuclear Power Plant Accident and the challenges for the future", IAEA Report on Severe Accident Management in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA, Vienna (2015).
[107] TOMINAGA, T., HACHIYA, M., AKASHI, M., Lessons learned from response to the accident at the TEPCO Fukushima Daiichi Nuclear Power Plant: from the viewpoint of radiation emergency medicine and combined disaster, Radiat. Emergency Med. **1** 1–2 (2012) 56–61.
[108] TANIGAWA, K., HASEGAWA, A., "Medical perspective", Radiation Disaster Medicine (TANIGAWA, K., CHHEM, R. K., Eds), Springer, Heidelberg (2014).
[109] NUCLEAR REGULATION AUTHORITY, WG3 question 7, 1st submission, official communication (2013).
[110] MINISTRY OF HEALTH, LABOUR AND WELFARE, Handling of Food Contaminated by Radioactivity (2011), http://www.mhlw.go.jp/english/topics/foodsafety/dl/food-110317.pdf
[111] MINISTRY OF HEALTH, LABOUR AND WELFARE, Issuance of Instruction to Restrict Distribution of Foods Concerned, in Relation to the Accident at Fukushima Nuclear Power Plant (2011), http://www.mhlw.go.jp/english/topics/2011eq/dl/food-110321.pdf
[112] MINISTRY OF HEALTH, LABOUR AND WELFARE, Restriction of Distribution and/or Consumption of Foods Concerned in Fukushima and Ibaraki Prefectures (2011), http://www.mhlw.go.jp/stf/houdou/2r98520000015wun-att/2r98520000015xym.pdf
[113] MINISTRY OF HEALTH, LABOUR AND WELFARE, Monitoring of Radioactive Contaminants for Agricultural and Livestock Products (2011), http://www.mhlw.go.jp/english/topics/2011eq/dl/food-110323.pdf
[114] MINISTRY OF HEALTH, LABOUR AND WELFARE, Handling of Provisional Regulation Values for Radioactive Iodine in Fishery Products (2011), http://www.mhlw.go.jp/english/topics/2011eq/dl/food-110405.pdf
[115] MINISTRY OF HEALTH, LABOUR AND WELFARE, New Standard Limits for Radionuclides in Foods (2012), http://www.mhlw.go.jp/english/topics/2011eq/dl/new_standard.pdf
[116] NATIONAL INSTITUTE OF RADIOLOGICAL SCIENCES, Telephone Consultations on Radiation Exposure: Report on Tabulated Results from the Year Following the TEPCO Fukushima Daiichi Nuclear Disaster (2014), http://www.nirs.go.jp/publication/irregular/pdf/nirs_m_265en.pdf
[117] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Issues in Public Communications Activities and Future Efforts Related to the Accident at the TEPCO's Fukushima Dai-ichi Nuclear Power Station, NISA, Tokyo (2012) (in Japanese).
[118] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Progress of the "Roadmap for Immediate Actions for the Assistance of Residents Affected by the Nuclear Incident" (2011), http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/110817_assistance_02.pdf
[119] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Progress of the "Roadmap for Immediate Actions for the Assistance of Residents Affected by the Nuclear Incident" (2011), http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/110920_assistance_02.pdf

[120] JAPAN EXTERNAL TRADE ORGANIZATION, Great East Japan Earthquake Influence on International Business (2014) (in Japanese),
www.jetro.go.jp/world/shinsai/20110318_11.html
[121] GOVERNMENT OF JAPAN, National Report of Japan to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (2011),
http://www.nsr.go.jp/english/cooperation/conventions/data/jc_4th.pdf
[122] NUCLEAR SAFETY COMMISSION, Near-term Policy to Ensure the Safety in Treating and Disposing Contaminated Waste around the Site of Fukushima Dai-ichi Nuclear Power Plants, NSC, Tokyo (2011).
[123] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Basic Policy for Emergency Response on Decontamination Work (2011),
http://www.kantei.go.jp/jp/singi/genshiryoku/dai19/19_03_gensai.pdf
[124] MINISTRY OF THE ENVIRONMENT, Act on Special Measures Concerning the Handling of Environmental Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District — Off the Pacific Ocean Earthquake that Occurred on March 11, 2011, Act No. 110 as of 2011 (Japan).
[125] ATOMIC ENERGY SOCIETY OF JAPAN, Final Report of the AESJ Investigation Committee (Announcement) (2014),
http://www.aesj.or.jp/en/announcement/finalreport20141119.pdf
[126] INDEPENDENT INVESTIGATION COMMISSION ON THE FUKUSHIMA NUCLEAR ACCIDENT, The Fukushima Daiichi Nuclear Power Station Disaster: Investigating the Myth and Reality, Routledge, London and New York (2014).
[127] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Application of the Commission's Recommendations for the Protection of People in Emergency Exposure Situations, Publication 109, Pergamon Press, Oxford and New York (2009).
[128] NUCLEAR SAFETY COMMISSION, Basic Policy of the Nuclear Safety Commission of Japan on Radiation Protection for Termination of Evacuation and Reconstruction (2011),
http://www.nsr.go.jp/archive/nsc/NSCenglish/geje/20110719suggest_4.pdf
[129] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, The 2007 Recommendations of the International Commission on Radiological Protection, Publication 103, Elsevier, Oxford (2007).
[130] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Roadmap for Immediate Actions for the Assistance of Nuclear Sufferers (2011),
http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/110517roadmap_assistance.pdf
[131] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Plan to Conduct Detailed Monitoring in Restricted Area and Planned Evacuation Zone (2011),
http://www.mext.go.jp/component/english/__icsFiles/afieldfile/2011/06/29/1304084_0613.pdf
[132] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Lifting the Evacuation-Prepared Area in Case of Emergency Designation (2011),
http://www.reconstruction.go.jp/topics/41gennshiryoku.pdf
[133] NUCLEAR EMERGENCY PREPAREDNESS COMMISSION, Nuclear Emergency Response Manual (2012) (in Japanese),
http://www.kantei.go.jp/jp/singi/genshiryoku_bousai/pdf/taisaku_manual.pdf
[134] NUCLEAR REGULATION AUTHORITY, National Report to the 6th Review Meeting of the Convention on Nuclear Safety (2013),
http://www.nsr.go.jp/english/cooperation/conventions/data/cns_6th.pdf
[135] NUCLEAR SAFETY COMMISSION, Interim Report for Reviewing "Regulatory Guide: Emergency Preparedness for Nuclear Facilities" (2012) (in Japanese),
http://www.nsr.go.jp/archive/nsc/NSCenglish/geje/20120322review_3.pdf
[136] NUCLEAR REGULATION AUTHORITY, Nuclear Emergency Response Guidelines (2012) (in Japanese),
http://www.nsr.go.jp/activity/bousai/data/130905_saitaishishin.pdf

[137] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, WORLD HEALTH ORGANIZATION, International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, Safety Series No. 115, IAEA, Vienna (1996). (This publication is superseded by GSR Part 3 (2014)).

[138] Convention on Early Notification of a Nuclear Accident, INFCIRC/335, IAEA, Vienna (1986).

[139] Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency, INFCIRC/336, IAEA, Vienna (1986).

[140] INTERNATIONAL ATOMIC ENERGY AGENCY, Joint Radiation Emergency Management Plan of the International Organizations, EPR-JPLAN, IAEA, Vienna (2010).

[141] INTERNATIONAL ATOMIC ENERGY AGENCY, Emergency Notification and Assistance Technical Operations Manual, EPR-ENATOM (2007), IAEA, Vienna (2007).

[142] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Response and Assistance Network (2010), http://www-ns.iaea.org/downloads/iec/info-brochures/13-27031-ranet.pdf

[143] IAEA Activities in Response to the Fukushima Accident, GOV/INF/2011/8, IAEA, Vienna (2011).

[144] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Action Plan on Nuclear Safety (2011), http://www.iaea.org/sites/default/files/actionplanns.pdf

[145] OECD NUCLEAR ENERGY AGENCY, Patterns in Governmental Decisions and Recommendations (GDR) Information Exchange during the Fukushima NPP Accident, NEA/CRPPH(2012)3, OECD, Paris (2012).

[146] WORLD HEALTH ORGANIZATION, Preliminary Dose Estimation from the Nuclear Accident after the 2011 Great East Japan Earthquake and Tsunami, WHO, Geneva (2012).

[147] WORLD HEALTH ORGANIZATION, Health Risk Assessment from the Nuclear Accident after the 2011 Great East Japan Earthquake and Tsunami, Based on a Preliminary Dose Estimation, WHO, Geneva (2013).

[148] UNITED NATIONS, Sources, Effects and Risks of Ionizing Radiation (Report to the General Assembly), UNSCEAR 2013 Report, Vol. I, Scientific Annex A: Levels and Effects of Radiation Exposure Due to the Nuclear Accident after the 2011 Great East-Japan Earthquake and Tsunami, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2014).

[149] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Report of ICRP Task Group 84 on Initial Lessons Learned from the Nuclear Power Plant Accident in Japan vis-à-vis the ICRP System of Radiological Protection, ICRP, Ottawa (2012).

[150] GONZÁLEZ, A.J., AKASHI, M., BOICE, J.D., Jr., CHINO, M., HOMMA, T., ISHIGURE, N., KAI, M., KUSUMI, S., LEE, J.-K., MENZEL, H.-G., NIWA, O., SAKAI, K., WEISS, W., YAMASHITA, S., YONEKURA, Y., Radiological protection issues arising during and after the Fukushima nuclear reactor accident, J. Radiol. Prot. **33** 3 (2013) 497–571.

[151] UNITED NATIONS, FAO/IAEA Food Database, UNSCEAR 2013 Report, Attachment C-8 of Annex A:, Levels and Effects of Radiation Exposure Due to the Nuclear Accident After the 2011 Great East-Japan Earthquake and Tsunami, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2014).

[152] WORLD METEOROLOGICAL ORGANIZATION, Evaluation of Meteorological Analyses for the Radionuclide Dispersion and Deposition from the Fukushima Daiichi Nuclear Power Plant Accident, WMO, Geneva (2013).

[153] OECD NUCLEAR ENERGY AGENCY, The Fukushima Daiichi Nuclear Power Plant Accident, OECD, Paris (2013).

[154] WORLD HEALTH ORGANIZATION, Guidelines for Drinking-water Quality, 3rd edn, WHO, Geneva (2008).

[155] General Standard for Contaminants and Toxins in Food and Feed of 1995, as last amended 2013, Codex Alimentarius Commission, http://www.fao.org/fileadmin/user_upload/agns/pdf/CXS_193e.pdf

[156] JAPAN HEALTH PHYSICS SOCIETY, Issues Associated with Radiation Protection after Fukushima Daiichi Nuclear Power Plant Disaster: Responses of and Recommendations from Japan Health Physics Society, JHPS (2012).

[157] YASUMURA, S., "Overview of Fukushima Health Management Survey", paper presented at 3rd Int. Expert Symp. on Beyond Radiation and Health Risk: Toward Resilience and Recovery, Fukushima (2014),
http://www.fmu.ac.jp/radiationhealth/symposium201409/media/5_S2_Yasumura_FINAL(0909).pdf
[158] FUKUSHIMA PREFECTURE, Agenda, 3rd Meeting of the Oversight Committee for the Fukushima Health Management Survey (2011) (in Japanese),
http://www.pref.fukushima.lg.jp/uploaded/attachment/6497.pdf
[159] SASAKAWA, Y., International Expert Symposium in Fukushima, September 2011, J. Radiol. Prot. **32** 1 (2012) E7–E8.
[160] Conclusions and recommendations of the International Expert Symposium in Fukushima: Radiation and Health Risks, J. Radiol. Prot. **31** 4 (2011) 381–384.
[161] FUKUSHIMA PREFECTURE, Terms of Reference of the Committee for the Fukushima Health Management Survey (2011) (in Japanese),
http://www.pref.fukushima.lg.jp/uploaded/attachment/65128.pdf
[162] FUKUSHIMA MEDICAL UNIVERSITY, Basic Survey (Radiation Dose Estimates), 19th Prefectural Oversight Committee Meeting for Fukushima Health Management Survey, Fukushima, Japan, (2015),
http://www.fmu.ac.jp/radiationhealth/results/media/19-1_Basic_Survey.pdf
[163] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, Radiation Quantities and Units, ICRU Rep. 33, Bethesda, MD (1980).
[164] INTERNATIONAL LABOUR ORGANIZATION, Convention Concerning the Protection of Workers against Ionising Radiations, No. 115, ILO, Geneva (1960).
[165] UNITED NATIONS, Sources and Effects of Ionizing Radiation (Report to the General Assembly), UNSCEAR 2008 Report, Vol. I, Annexes A and B, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2010).
[166] NATIONAL COUNCIL ON RADIATION PROTECTION MEASUREMENTS, Uncertainties in Fatal Cancer Risk Estimates Used in Radiation Protection, NCRP Rep. No. 126, NCRP, Bethesda, MA (1997).
[167] UNITED NATIONS, Report of the United Nations Scientific Committee on the Effects of Atomic Radiation, A/67/46, UN, New York (2012).
[168] UNITED NATIONS, Sources and Effects of Ionizing Radiation (Report to the General Assembly), UNSCEAR 1977 Report, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (1977).
[169] INTERNATIONAL ATOMIC ENERGY AGENCY, The International Chernobyl Project: Technical Report, IAEA, Vienna (1991).
[170] ESLINGER, P.W., et al., Source term estimation of radioxenon released from the Fukushima Dai-ichi nuclear reactors using measured air concentrations and atmospheric transport modeling, J. Environ. Radioact. **127** (2014) 127–132.
[171] STOHL, A., et al., Xenon-133 and caesium-137 releases into the atmosphere from the Fukushima Dai-ichi nuclear power plant: Determination of the source term, atmospheric dispersion, and deposition, Atmos. Chem. Phys. **12** 5 (2012) 2313–2343.
[172] BOWYER, T. W., et al., Elevated radioxenon detected remotely following the Fukushima Nuclear accident, J. Environ. Radioact. **102** 7 (2011) 681–687.
[173] SCHÖPPNER, M., et al., Estimation of the time-dependent radioactive source-term from the Fukushima nuclear power plant accident using atmospheric transport modelling, J. Environ. Radioact. **114** (2012) 10–14.
[174] TERADA, H., KATATA, G., CHINO, M., NAGAI, H., Atmospheric discharge and dispersion of radionuclides during the Fukushima Dai-ichi nuclear power plant accident. Part II: Verification of the source term and analysis of regional-scale atmospheric dispersion, J. Environ. Radioact. **112** (2012) 141–154.
[175] SCIENCE COUNCIL OF JAPAN, A Review of the Model Comparison of Transportation and Deposition of Radioactive Materials Released to the Environment as a Result of the Tokyo Electric Power Company's Fukushima Daiichi Nuclear Power Plant Accident (2014),
http://www.jpgu.org/scj/report/20140902scj_report_e.pdf
[176] CHINO, M., et al., Preliminary estimation of release amounts of ^{131}I and ^{137}Cs accidentally discharged from the Fukushima Daiichi nuclear power plant into the atmosphere, J. Nucl. Sci. Technol. **48** 7 (2011) 1129–1134.

[177] BUESSELER, K., AOYAMA, M., FUKASAWA, M., Impacts of the Fukushima nuclear power plants on marine radioactivity, Environ. Sci. Technol. **45** 23 (2011) 9931–9935.

[178] EUROPEAN COMMISSION, INTERNATIONAL ATOMIC ENERGY AGENCY, WORLD HEALTH ORGANIZATION, One Decade after Chernobyl: Summing up the Consequences of the Accident, IAEA, Vienna (1996).

[179] Chernobyl: Looking Back to Go Forward (Proc. Int. Conf Vienna, 2005), IAEA, Vienna (2005).

[180] INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE, Accident de la Centrale de Fukushima Daiichi: Modélisation de la Dispersion des Rejets Radioactifs dans l'Atmosphère à l'Échelle Mondiale (2011),
http://www.irsn.fr/FR/popup/Pages/irsn-meteo-france_30mars.aspx

[181] Exploring the Impacts of the Fukushima Dai-ichi Nuclear Power Plant on the Ocean (Proc. Fukushima Ocean Impacts Symp. Tokyo, 2012), Woods Hole Oceanographic Institution, Woods Hole, MA (2012).

[182] MADIGAN, D.J., BAUMANN, Z., FISHER, N.S., Pacific bluefin tuna transport Fukushima-derived radionuclides from Japan to California, Proceedings of the National Academy of Sciences **109** 24 (2012) 9483-9486.

[183] MASUMOTO, Y., "Ocean models: How far/fast does Fukushima contamination travel?", Exploring the Impacts of the Fukushima Dai-ichi Nuclear Power Plants on the Ocean (Proc. Fukushima Ocean Impacts Symp.Tokyo, 2012), Woods Hole Oceanographic Institution, Woods Hole, MA (2012).

[184] MASUMOTO, Y., et al., Oceanic dispersion simulations of ^{137}Cs released from the Fukushima Daiichi nuclear power plant, Elements **8** 3 (2012) 207–212.

[185] HONDA, M.C., AONO, T., AOYAMA, M., Dispersion of artificial caesium-134 and -137 in the Western North Pacific one month after the Fukushima accident, Geochem. J. **46** 6 (2012) e1–9.

[186] RYPINA, I.I., et al., Short-term dispersal of Fukushima-derived radionuclides off Japan: modeling efforts and model-data intercomparison, Biogeosciences **10** 1 (2013) 4973–4990.

[187] AOYAMA, M., HIROSE, K., IGARASHI, Y., Re-construction and updating our understanding on the global weapons tests ^{137}Cs fallout, J. Environ. Monitor. **8** 4 (2006) 431–438.

[188] BUESSELER, K., AOYAMA, M., "Fukushima results", Exploring the impacts of the Fukushima Dai-ichi Nuclear Power Plants on the Ocean (Proc. Fukushima Ocean Impacts Symp. Tokyo, 2012), Woods Hole Oceanographic Institution, Woods Hole, MA (2012).

[189] NUCLEAR REGULATION AUTHORITY, Radiation Monitoring Information. Monitoring Information of Environmental Radioactivity Level, NRA (2015) (in Japanese),
http://radioactivity.nsr.go.jp/ja/list/191/list-1.html

[190] UNITED NATIONS, Sources and Effects of Ionizing Radiation (Report to the General Assembly), UNSCEAR 2000 Report, Vol. I, Sources, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2000).

[191] NUCLEAR REGULATION AUTHORITY, Reading of Radioactivity Level in Fallout by Prefecture (2011-2015),
http://radioactivity.nsr.go.jp/en/list/194/list-1.html

[192] NUCLEAR REGULATION AUTHORITY, Airborne Monitoring,
http://radioactivity.nsr.go.jp/en/list/278/list-1.html

[193] MINISTRY OF HEALTH, LABOUR AND WELFARE, Notice No. 0315 Article 1 of the Department of Food Safety (2012),
http://www.mhlw.go.jp/english/topics/2011eq/dl/food-120821_1.pdf

[194] INTERNATIONAL ATOMIC ENERGY AGENCY, Mission Report: Project NSRW 9/13 Assistance in the Use of Radiation Monitoring Data to Develop Maps to be Made Available to the Public, Fukushima Prefecture, 16–19 December 2013 (unpublished).

[195] MINISTRY OF HEALTH, LABOUR AND WELFARE, The Survey Results of Radioactive Materials in Tap Water, MHLW, Tokyo (2011).

[196] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, 1990 Recommendations of the International Commission on Radiological Protection, Publication 60, Pergamon Press, Oxford and New York (1991).

[197] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Application of the Commission's Recommendations to the Protection of People Living in Long-term Contaminated Areas After a Nuclear Accident or a Radiation Emergency, Publication 111, Elsevier, Oxford (2009).

[198] EUROPEAN COMMISSION, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, WORLD HEALTH ORGANIZATION, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, IAEA Safety Standards Series No. GSR Part 3, IAEA, Vienna (2014).

[199] AKASHI, M., TOMINAGA, T., HACHIYA, M., TATSUZAKI, H., "Medical management of the consequences of the Fukushima nuclear plant incident", Medical Basis for Radiation Accident Preparedness (Proc. 5th Int. REAC/TS Symp. Oak Ridge, 2013), Oak Ridge, TN (2013).

[200] YASUMURA, S., GOTO, A., YAMAZAKI, S., REICH, M.R., Excess mortality among relocated institutionalized elderly after the Fukushima nuclear disaster, Public Health **127** 2 (2013) 186–188.

[201] NOMURA, S., et al., Mortality risk amongst nursing home residents evacuated after the Fukushima Nuclear accident: A retrospective cohort study, PLoS ONE **8** 3 (2013) e60192.

[202] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Principles for Intervention for Protection of the Public in a Radiological Emergency, Publication 63, Pergamon Press, Oxford and New York (1993).

[203] MINISTRY OF HEALTH, LABOUR AND WELFARE, Publication and Enforcement of “the Ministerial Ordinance for Abolishment of Exemption in the Ordinance on Prevention of Ionizing Radiation Hazards in Response to the Situation Resulting from the Tohoku–Pacific Ocean Earthquake in 2011” (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/rp/pr_111216.html

[204] AKAHANE, K., et al., NIRS external dose estimation system for Fukushima residents after the Fukushima Dai-ichi NPP accident, Sci. Rep. **3** (2013) 1670.

[205] ISHIKAWA, T., “The basic survey: Estimation of external doses to residents in Fukushima Prefecture”, paper presented at 3rd Int. Expert Symp. on Beyond Radiation and Health Risk: Toward Resilience and Recovery, Fukushima, 2014, http://www.fmu.ac.jp/radiationhealth/symposium201409/media/6_S2_Ishikawa.pdf

[206] NAGATAKI, S., TAKAMURA, N., KAMIYA, K., AKASHI, M., Measurements of individual radiation doses in residents living around the Fukushima nuclear power plant, Radiat. Res. **180** 5 (2013) 439–447.

[207] FUKUSHIMA MEDICAL UNIVERSITY, “Response rates to the basic survey by district. Data as of 31 December 2014” (Proc. 18th Prefectural Oversight Committee Meeting for Fukushima Health Management Survey Fukushima, 2015), https://www.fmu.ac.jp/radiationhealth/results/media/18-1_Basic_Survey_Appendix.pdf

[208] FUKUSHIMA MEDICAL UNIVERSITY, “Basic survey (radiation dose estimates)” (Proc. 18th Prefectural Oversight Committee Meeting for Fukushima Health Management Survey Fukushima, 2015) (2015), http://www.fmu.ac.jp/radiationhealth/results/media/18-1_Basic_Survey.pdf

[209] DATE CITY, Newsletter on Recovery and Revival in Date City No. 8: Analyses on Measurement of Annual Dose from External Exposure (2013) (in Japanese), http://www.city.date.fukushima.jp/uploaded/attachment/10035.pdf

[210] TSUBOKURA, M., et al., Absence of internal radiation contamination by radioactive cesium among children affected by the Fukushima Daiichi nuclear power plant disaster, Health Phys **108** 1 (2015) 39–43.

[211] HAYANO, R.S., et al., Whole-body counter survey results 4 months after the Fukushima Dai-ichi NPP accident in Minamisoma City, Fukushima, J. Radiol. Prot. **34** 4 (2014) 787.

[212] HAYANO, R. S., et al., Internal radiocesium contamination of adults and children in Fukushima 7 to 20 months after the Fukushima NPP accident as measured by extensive whole-body-counter surveys, Proc. Jpn Acad. Ser. B Phys. Biol. Sci. **89** 4 (2013) 157–163.

[213] MATSUDA, N., et al., Assessment of internal exposure doses in Fukushima by a whole body counter within one month after the nuclear power plant accident, J. Radiat. Res. **179** 6 (2013) 663–668.

[214] KIM, E., et al., “Screening survey on thyroid exposure for children after the Fukushima Daiichi nuclear power station accident”, Reconstruction of Early Internal Dose in the TEPCO Fukushima Daiichi Nuclear Power Station Accident (Proc. 1st NIRS Symp.) (KURIHARA, O., AKAHANE, K., FUKUDA, S., MIYAHARA, N., YONAI, S., Eds), National Institute of Radiological Sciences, Chiba (2012) 59–66.

[215] TOKYO ELECTRIC POWER COMPANY, Updated worker doses, official communication (2015).

[216] TOKYO ELECTRIC POWER COMPANY, Evaluation of the Exposure Dose of Workers at the Fukushima Daiichi Nuclear Power Station. Attachment: Distribution of Thyroid Equivalent Doses (2015),
http://www.tepco.co.jp/en/press/corp-com/release/2015/1248073_6844.html
[217] MINISTRY OF HEALTH, LABOUR AND WELFARE, Re-evaluation Results of Committed Doses for Emergency Workers at the TEPCO Fukushima Daiichi Nuclear Power Plant (2013),
http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/rp/pr_130705_a02.pdf
[218] YASUI, S., Governmental re-evaluation of the committed effective dose received by emergency workers at the TEPCO Fukushima Daiichi NPP accident, J. Occupat. Environ. Hyg. **12** 5 (2015) D60–D70.
[219] DEFENSE THREAT REDUCTION AGENCY, Radiation Dose Assessments for Shore-based Individuals in Operation Tomodachi, DTRA-TR-12-001, DTRA, Fort Belvoir, VA (2012).
[220] HASHIMOTO, S., et al., "First two-year result of the comprehensive health check as one facet of the Fukushima Health Management Survey" paper presented at 3rd Int. Expert Symp. on Beyond Radiation and Health Risk: Toward Resilience and Recovery, Fukushima, 2014,
http://www.fmu.ac.jp/radiationhealth/symposium201409/media/7_S2_Hashimoto_FINAL(0909).pdf
[221] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, ICRP Statement on Tissue Reactions/Early and Late Effects of Radiation in Normal Tissues and Organs: Threshold Doses for Tissue Reactions in a Radiation Protection Context, Publication 118, Elsevier, Oxford (2012).
[222] TOKYO ELECTRIC POWER COMPANY, Result of the Investigation on Exposure to Radiation of Workers from Cooperative Companies at Unit 3 in Fukushima Daiichi Nuclear Power Station (2011),
http://www.tepco.co.jp/en/press/corp-com/release/11032503-e.html
[223] UNITED NATIONS, Report of the United Nations Scientific Committee on the Effects of Atomic Radiation, A/68/46, UN, New York (2013).
[224] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Low-dose Extrapolation of Radiation-related Cancer Risk, Publication 99, Elsevier, Oxford (2005).
[225] UNITED NATIONS, Report of the United Nations Scientific Committee on the Effects of Atomic Radiation, A/63/46, UN, New York (2008).
[226] SUZUKI, S., et al., "Three-Year Results and Future Scope of the Fukushima Thyroid Ultrasound Examination after the Fukushima NPP Accident", paper presented at 3rd Int. Expert Symp. on Beyond Radiation and Health Risk: Toward Resilience and Recovery, Fukushima (2014),
http://www.fmu.ac.jp/radiationhealth/symposium201409/media/9_S2_Suzuki_FINAL(0909).pdf
[227] HAYASHIDA, N., et al., Thyroid ultrasound findings in a follow-up survey of children from three Japanese Prefectures: Aomori, Yamanashi, and Nagasaki, Sci. Rep. **5** (2015).
[228] FUKUSHIMA PREFECTURE, Proc. 18th Prefectural Oversight Committee Meeting for Fukushima Health Management Survey (2015),
http://www.fmu.ac.jp/radiationhealth/results/20150212_Thyroid_Ultrasound_Examination.html
[229] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Pregnancy and Medical Radiation, Publication 84, Pergamon Press, Oxford and New York (2000).
[230] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Doses to the Embryo and Foetus from Intakes of Radionuclides by the Mother, Publication 88, Pergamon Press, Oxford and New York (2001).
[231] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Biological Effects after Prenatal Irradiation (Embryo and Foetus), Publication 90, Pergamon Press, Oxford and New York (2003).
[232] NOMURA, Y., "Pregnancy and birth survey (by the Radiation Medical Science Center for the Fukushima Health Management Survey)", paper presented at 3rd Int. Expert Symp. on Beyond Radiation and Health Risk: Toward Resilience and Recovery, Fukushima, 2014,
http://www.fmu.ac.jp/radiationhealth/symposium201409/media/10_S2_Nomura_FINAL(0909).pdf
[233] NOMURA, Y., FUJIMORI, K., Survey of pregnant women in Fukushima Prefecture and future issues, Fukushima J. Med. Sci. **60** 2 (2014) 213.
[234] YASUMURA, S., et al., Study protocol for the Fukushima Health Management Survey, J. Epidemiol. **22** 5 (2012) 375–383.
[235] KAWAKAMI, N., Mental Health of Residents Living in Shelters, Japanese Association of Epidemiology, Tokyo (2014).

[236] YABE, H., et al., Psychological distress after the Great East Japan Earthquake and Fukushima Daiichi nuclear power plant accident: results of a Mental Health and Lifestyle Survey through the Fukushima Health Management Survey in FY2011 and FY2012, Fukushima J. Med. Sci. **60** 1 (2014) 57–67.
[237] KAWAKAMI, N., TSUCHIYA, M., UMEDA, M., KOENEN, K.C., KESSLER, R.C., Trauma and posttraumatic stress disorder in Japan: results from the World Mental Health Japan Survey, J. Psychiatr. Res. **53** (2014) 157–165.
[238] IWADARE, Y., et al., Posttraumatic symptoms in elementary and junior high school children after the 2011 Japan earthquake and tsunami: Symptom severity and recovery vary by age and sex, J. Pediatrics **164** 4 (2014) 917–921.
[239] BROMET, E.J., Emotional consequences of nuclear power plant disasters, Health Phys. **106** 2 (2014) 206–210.
[240] GOTO, A., et al., Maternal confidence of Fukushima mothers before and after the nuclear power plant disaster in Northeast Japan: analyses of municipal health records, J. Commun. Healthcare **7** 2 (2014) 106–116.
[241] BROMET, E. J., et al., Cross-national epidemiology of DSM-IV major depressive episode, BMC Med. **9** 1 (2011) 90.
[242] SHIGEMURA, J., TANIGAWA, T., SAITO, I., NOMURA, S., Psychological distress in workers at the Fukushima nuclear power plants, JAMA **308** 7 (2012) 667–669.
[243] SHIGEMURA, J., et al., Associations between disaster exposures, peritraumatic distress, and posttraumatic stress responses in Fukushima nuclear plant workers following the 2011 nuclear accident: the Fukushima NEWS project study, PLoS One **9** 2 (2014) e87516.
[244] MATSUOKA, Y., et al., Concern over radiation exposure and psychological distress among rescue workers following the Great East Japan Earthquake, BMC Public Health **12** (2012) 249.
[245] BROMET, E.J., Mental health consequences of the Chernobyl disaster, J Radiol Prot **32** 1 (2012) N71–75.
[246] BROMET, E.J., HAVENAAR, J. M., Psychological and perceived health effects of the Chernobyl disaster: A 20-year review, Health Phys **93** 5 (2007) 516–521.
[247] BROMET, E.J., HAVENAAR, J. M., GUEY, L. T., A 25 year retrospective review of the psychological consequences of the Chernobyl accident, Clin. Oncol. **23** 4 (2011) 297–305.
[248] MAEDA, M., et al., “Psychological effects on people in Fukushima: Results of a mental health and lifestyle survey”, paper presented at 3rd Int. Expert Symp. on Beyond Radiation and Health Risk: Toward Resilience and Recovery, Fukushima, 2014,
http://www.fmu.ac.jp/radiationhealth/symposium201409/media/8_S2_Maeda_FINAL(0909).pdf
[249] KESSLER, R.C., et al., Screening for serious mental illness in the general population, Arch. Gen. Psychiat. **60** 2 (2003) 184–189.
[250] BLANCHARD, E.B., JONES-ALEXANDER, J., BUCKLEY, T.C., FORNERIS, C.A., Psychometric properties of the PTSD checklist (PCL), Behav. Res. Ther. **34** 8 (1996) 669–673.
[251] EWING, J.A., Detecting alcoholism. The CAGE questionnaire, JAMA **252** 14 (1984) 1905–1907.
[252] GOODMAN, R., Psychometric properties of the strengths and difficulties questionnaire, J. Am. Acad. Child Adolesc. Psychiatry **40** 11 (2001) 1337–1345.
[253] MATSUISHI, T., et al., Scale properties of the Japanese version of the strengths and difficulties questionnaire (SDQ): A study of infant and school children in community samples, Brain Dev. **30** 6 (2008) 410–415.
[254] OGURI, K., et al., Hadal disturbance in the Japan Trench induced by the 2011 Tohoku–Oki earthquake, Sci. Rep. **3** (2013).
[255] BIODIVERSITY CENTER OF JAPAN, Official web site about the effect of the earthquake and the tsunami (in Japanese),
http://www.shiokaze.biodic.go.jp
[256] NAKAJIMA, H., KOARAI, M., Assessment of tsunami flood situation from the Great East Japan Earthquake, Bull. Geosp. Inf. Auth. Jpn. **59** (2011) 55–66.
[257] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, A Framework for Assessing the Impact of Ionising Radiation on Non-human Species, Publication 91, Pergamon Press, Oxford and New York (2003).

[258] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Protection of the Environment Under Different Exposure Situations, Publication 124, Pergamon Press, Oxford and New York (2014).
[259] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Environmental Protection: Transfer Parameters for Reference Animals and Plants, Publication 114, Elsevier, Oxford (2009).
[260] LINKOV, I., BURMISTROV, D., Model uncertainty and choices made by modelers: Lessons learned from the International Atomic Energy Agency model intercomparisons, Risk Anal. **23** 6 (2003) 1297–1308.
[261] UNITED NATIONS, Sources and Effects of Ionizing Radiation (Report to the General Assembly), UNSCEAR 2008 Report, Vol. II, Scientific Annexes C, D and E, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2011).
[262] UNITED NATIONS, Sources and Effects of Ionizing Radiation (Report to the General Assembly), UNSCEAR 1996 Report, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (1996).
[263] INTERNATIONAL ATOMIC ENERGY AGENCY, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards (Interim Edition), IAEA Safety Standards Series No. GSR Part 3 (Interim), IAEA, Vienna (2011). (This publication is superseded by GSR Part 3 (2014)).
[264] INTERNATIONAL ATOMIC ENERGY AGENCY, Summary Report of the Preliminary Findings of the IAEA Mission on Remediation of Large Contaminated Areas Off-site the Fukushima Dai-ichi NPP (2011),
https://www.iaea.org/sites/default/files/preliminaryfindings2011.pdf
[265] INTERNATIONAL ATOMIC ENERGY AGENCY, The Follow-up IAEA International Mission on Remediation of Large Contaminated Areas Off-Site of the Fukushima Daiichi Nuclear Power Plant (2013),
https://www.iaea.org/sites/default/files/final_report230114.pdf
[266] MINISTRY OF THE ENVIRONMENT, Basic Principles of the Act on Special Measures Concerning the Handling of Environment Pollution by Radioactive Materials Discharged from the Nuclear Power Station Accident Associated with the Tohoku District—Off the Pacific Ocean Earthquake that Occurred on March 11, 2011 (2011),
http://josen.env.go.jp/en/framework/pdf/basic_principles.pdf
[267] GOLIKOV, V., et al., Evaluation of conversion coefficients from measurable to risk quantities for external exposure over contaminated soil by use of physical human phantoms, Radiat. Environ. Biophys **46** 4 (2007) 375–382.
[268] CABINET OFFICE, "Designating and rearranging the areas of evacuation", paper presented at Follow-up IAEA International Mission on Remediation of Large Contaminated Areas Off-Site the Fukushima Daiichi Nuclear Power Plant, Tokyo and Fukushima Prefecture, 2013.
[269] FUKUSHIMA PREFECTURE, Steps for Revitalization in Fukushima (2014),
http://www.pref.fukushima.lg.jp.e.od.hp.transer.com/sec/11015b/fukkoukeikaku1081.html
[270] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Areas to which Evacuation Orders have been Issued (2013),
http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/20130807_01.pdf
[271] JAPAN ATOMIC ENERGY AGENCY, Use of Knowledge and Experience Gained from the Fukushima Daiichi Nuclear Power Station Accident to Establish the Technical Basis for Strategic Off-Site Response (2015),
http://jolissrch-inter.tokai-sc.jaea.go.jp/search/servlet/search?5049878
[272] JAPAN ATOMIC ENERGY AGENCY, Remediation of Contaminated Areas in the Aftermath of the Accident at the Fukushima Daiichi Nuclear Power Station: Overview, Analysis and Lessons Learned, Part 1: A Report on the "Decontamination Pilot Project", JAEA-Review 2014-051, JAEA, Tokyo (2015).
[273] MINISTRY OF THE ENVIRONMENT, Progress on Off-site Clean-up Efforts in Japan (2015),
http://josen.env.go.jp/en/pdf/progressseet_progress_on_cleanup_efforts.pdf?150113
[274] MINISTRY OF THE ENVIRONMENT, Unit prices for decontamination in the SDAs directly controlled by the national government, official communication (2015).
[275] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Mid-and-Long-Term Roadmap towards the Decommissioning of Fukushima Daiichi Nuclear Power Station Units 1-4, TEPCO (2011),
http://www.meti.go.jp/english/earthquake/nuclear/decommissioning/pdf/111221_02.pdf

[276] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Revised Mid-and-Long-Term Roadmap towards the Decommissioning of Fukushima Daiichi Nuclear Power Station Units 1-4 (2013), http://josen.env.go.jp/en/documents/pdf/workshop_july_17-18_2013_02.pdf
[277] INTER-MINISTERIAL COUNCIL FOR CONTAMINATED WATER AND DECOMMISSIONING ISSUES, Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station (2015).
[278] Act for Establishment of the Nuclear Regulation Authority, Act No. 47, 27 June, 2012, as amended by Act No. 82 of 2013 (Japan), https://www.nsr.go.jp/data/000067231.pdf
[279] TOKYO ELECTRIC POWER COMPANY, Implementation Plan of the Measures to be taken at Fukushima Daiichi Nuclear Power Station Designated as a Specified Reactor Facility (Outline) (2012), http://www.tepco.co.jp/en/nu/fukushima-np/images/handouts_12120701-e.pdf
[280] NUCLEAR REGULATION AUTHORITY, Measures for Mid-Term Risk Reduction at TEPCO’s Fukushima Daiichi NPS (2015), http://www.nsr.go.jp/data/000098679.pdf
[281] CONTAMINATED WATER TREATMENT MEASURES COMMITTEE, Measures for the Prevention of Groundwater Inflow, TEPCO (2012).
[282] GOVERNMENT OF JAPAN, TOKYO ELECTRIC POWER COMPANY, Progress Status and Future Challenges of Mid-to-Long-Term Roadmap towards the Decommissioning of Units 1–4 of TEPCO Fukushima Daiichi Nuclear Power Plant (2012), http://www.tepco.co.jp/en/nu/fukushima-np/roadmap/images/m121203-e.pdf
[283] TOKYO ELECTRIC POWER COMPANY, Comments received on Section 5, official communication (2 March 2015).
[284] TOKYO ELECTRIC POWER COMPANY, Contaminated Water Treatment (2015), http://www.tepco.co.jp/en/decommision/planaction/alps/index-e.html
[285] TOKYO ELECTRIC POWER COMPANY, Fukushima Daiichi NPS Prompt Report 2014: Bypass of Clean Groundwater to Ocean Starts (2014), http://www.tepco.co.jp/en/press/corp-com/release/2014/1236566_5892.html
[286] TOKYO ELECTRIC POWER COMPANY, "Measures to stop or reduce ingress of groundwater into reactor and turbine buildings", paper presented at IAEA International Peer Review Mission on Mid-and-Long-Term Roadmap Towards the Decommissioning of TEPCO’s Fukushima Daiichi Nuclear Power Station Units 1-4 (Second Mission), Tokyo and Fukushima Prefecture, 2013.
[287] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Fact Sheet: Overview of Contaminated Water Issue at TEPCO’s Fukushima Daiichi Nuclear Power Station, Agency for Natural Resources and Energy (2013), http://www.meti.go.jp/english/earthquake/nuclear/decommissioning/pdf/20130822_01.pdf
[288] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA International Peer Review Mission on Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO’s Fukushima Daiichi Nuclear Power Station Units 1–4 (Second Mission) (2014), http://www.meti.go.jp/press/2013/02/20140213003/20140213003-2.pdf
[289] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA International Peer Review Mission on Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4 (Third Mission) (2015), https://www.iaea.org/sites/default/files/missionreport170215.pdf
[290] TOKYO ELECTRIC POWER COMPANY, Fuel Removal of the Unit 4 Spent Fuel Pool of the Fukushima Daiichi NPP Completed (2014) (in Japanese), http://www.tepco.co.jp/nu/fukushima-np/handouts/2014/images/handouts_141222_04-j.pdf
[291] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Mid-and-Long-Term Roadmap Towards the Decommissioning of TEPCO’s Fukushima Daiichi Nuclear Power Station Units 1–4 (2013), http://www.meti.go.jp/english/press/2013/pdf/0627_01.pdf
[292] INTERNATIONAL ATOMIC ENERGY AGENCY, Decommissioning of Facilities Using Radioactive Material, IAEA Safety Standards Series No. WS-R-5, IAEA, Vienna (2006). (This publication is superseded by GSR Part 6 (2014)).
[293] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Decommissioning and Remediation after a Nuclear Accident, IAEA, Vienna (2013).

[294] OECD NUCLEAR ENERGY AGENCY, Nucl. Law Bull. **90** 2 (2012).
[295] GOVERNMENT OF JAPAN, Flow chart of specified waste and contaminated soil management in other prefectures, official communication (2015).
[296] TOKYO ELECTRIC POWER COMPANY, Mid-and-Long-Term Plans for Solid Waste Storage of the Fukushima Daiichi Nuclear Power Station (Draft) (2014) (in Japanese), http://www.tepco.co.jp/nu/fukushima-np/roadmap/images/l140407_05-j.pdf
[297] TOKYO ELECTRIC POWER COMPANY, Installation of Facilities for Temporary Storage Dry Casks (2014) (in Japanese), http://www.meti.go.jp/earthquake/nuclear/pdf/120625/120625_02cc.pdf
[298] TOKYO ELECTRIC POWER COMPANY, A Mid-and-long-term plan for storage of solid wastes in Fukushima Daiichi NPS, official communication (2014).
[299] TOKYO ELECTRIC POWER COMPANY, "Radioactive Waste Management — Toward the decommissioning of Fukushima Daiichi Nuclear Power Station Units 1–4", paper presented at IAEA International Peer Review Mission on Mid-and-Long-Term Roadmap Towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4 (Second Mission), Tokyo and Fukushima Prefecture, 2013.
[300] TOKYO ELECTRIC POWER COMPANY, Progress Status of Mid-and-Long-Term Roadmap Towards the Decommissioning of Fukushima Daiichi Nuclear Power Station Units 1–4 (2012), http://www.tepco.co.jp/en/nu/fukushima-np/roadmap/images/m120730-e.pdf
[301] SECRETARIAT OF THE TEAM FOR COUNTERMEASURES FOR DECOMMISSIONING AND CONTAMINATED WATER TREATMENT, Summary of Decommissioning and Contaminated Water Management (2014), http://www.meti.go.jp/english/earthquake/nuclear/decommissioning/pdf/20140529-e.pdf
[302] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Reports from ICRP Dialogue Initiatives (2014), http://www.icrp.org/page.asp?id=189
[303] JAPAN EXTERNAL TRADE ORGANIZATION, 2011 JETRO Global Trade and Investment Report: International Business as a Catalyst for Japan's Reconstruction, JETRO, Tokyo (2011).
[304] FISHERIES AGENCY, The Leakage of Contaminated Water at TEPCO's Fukushima Daiichi Nuclear Power Station and the Safety of Fishery Products (2015).
[305] FOOD STANDARDS AGENCY, Import of Feed and Food Originating in or Consigned from Japan (2012), http://www.food.gov.uk/business-industry/imports/banned_restricted/japan#.UKS7deQ0V8E
[306] JAPAN EXTERNAL TRADE ORGANIZATION, JETRO Global Trade and Investment Report — Overview (2014), http://www.jetro.go.jp/en/reports/white_paper/trade_invest_2014.pdf
[307] Act on Compensation for Nuclear Damage, 1961, Act. Nr. 147, as amended by Act Nr. 19 in 2009.
[308] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, DISPUTE RECONCILIATION COMMITTEE FOR NUCLEAR DAMAGE COMPENSATION, Interim Guidelines On Determination of the Scope of Nuclear Damage Resulting from the Accident at The Tokyo Electric Power Company Fukushima Daiichi and Daini Nuclear Power Plants (2011) (in Japanese), http://www.mext.go.jp/b_menu/shingi/chousa/kaihatu/016/houkoku/__icsFiles/afieldfile/2011/08/17/1309452_1_2.pdf
[309] TOKYO ELECTRIC POWER COMPANY, Compensation for Additional Costs Resulting from Early Return after the Evacuation Order is Lifted (2014) (in Japanese), http://www.tepco.co.jp/cc/press/2014/1235026_5851.html
[310] PERKO, T., VALUCH, J., NAGY, A., LAMMERS, P., MAYS, C., Overview of Mass and New Media Treatment of Ionizing Radiation Topics: The Case of Fukushima, EAGLE Coordination Project (2013), http://eagle.sckcen.be/en/Deliverables
[311] FUKUSHIMA PREFECTURE, Steps for Revitalization in Fukushima, Fukushima Prefecture (2013).
[312] MINISTRY OF THE ENVIRONMENT, FUKUSHIMA PREFECTURE, Decontamination Information Plaza (2013).
[313] MINISTRY OF THE ENVIRONMENT, "Stakeholder communication overview for decontamination", paper presented at Follow-up IAEA International Mission on Remediation of Large Contaminated Areas Off-site of the Fukushima Daiichi Nuclear Power Plant, Tokyo and Fukushima Prefecture, 2013.

[314] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Enhancing Transparency and Communication Effectiveness in the Event of a Nuclear or Radiological Emergency, IAEA, Vienna (2012).
[315] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Director General Calls for High Level Conference to Strengthen Nuclear Safety (2011), https://www.iaea.org/newscenter/news/iaea-director-general-calls-high-level-conference-strengthen-nuclear-safety
[316] INTERNATIONAL ATOMIC ENERGY AGENCY, Final Report of the International Mission on Remediation of Large Contaminated Areas Off-site the Fukushima Dai-ichi NPP (2011), http://www.mofa.go.jp/mofaj/saigai/pdfs/iaea_mission_1110_en.pdf
[317] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Mission to Review NISA's Approach to the Comprehensive Assessments for the Safety of Existing Power Reactor Facilities Conducted in Japan (2012), https://www.iaea.org/sites/default/files/nisamissionreport2012.pdf
[318] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Mission to Onagawa Nuclear Power Station to Examine the Performance of Systems, Structures and Components Following the Great East Japanese Earthquake and Tsunami (2012).
[319] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA International Peer Review Mission on Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4 (2013), http://www.iaea.org/sites/default/files/missionreport220513.pdf
[320] Declaration by the IAEA Ministerial Conference on Nuclear Safety in Vienna on 20 June 2011 INFCIRC/821, IAEA, Vienna (2011).
[321] Measures to Strengthen International Cooperation in Nuclear, Radiation, Transport and Waste Safety, Resolution GOV/2013/32-GC(57)/RES/9, IAEA, Vienna (2013).
[322] Progress in the Implementation of the IAEA Action Plan on Nuclear Safety, GOV/INF/2012/11-GC(56)/INF/5, IAEA, Vienna (2012).
[323] Progress in the Implementation of the IAEA Action Plan on Nuclear Safety, GOV/INF/2013/8-GC(57)/INF/5, IAEA, Vienna (2013).
[324] Progress in the Implementation of the IAEA Action Plan on Nuclear Safety, GOV/INF/2014/15-GC(58)/INF/7, IAEA, Vienna (2014).
[325] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Protection against Extreme Earthquakes and Tsunamis in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA, Vienna (2012).
[326] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Radiation Protection After the Fukushima Daiichi Accident: Promoting Confidence and Understanding, IAEA, Vienna (2014).
[327] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Preparedness and Response for a Nuclear or Radiological Emergency in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA, Vienna (2013).
[328] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Strengthening Nuclear Regulatory Effectiveness in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA, Vienna (2013).
[329] Memorandum of Cooperation between Fukushima Prefecture and the International Atomic Energy Agency Following the Accident at TEPCO's Fukushima Daiichi Nuclear Power Station (2012), http://www.mofa.go.jp/policy/energy/fukushima_2012/pdfs/fukushima_iaea_en_04.pdf
[330] Practical Arrangements between Fukushima Prefecture and the International Atomic Energy Agency on Cooperation in the Area of Radiation Monitoring and Remediation (2012), http://www.mofa.go.jp/policy/energy/fukushima_2012/pdfs/fukushima_iaea_en_05.pdf
[331] Practical Arrangements between Fukushima Medical University and the International Atomic Energy Agency on Cooperation in the Area of Human Health (2012), http://www.mofa.go.jp/policy/energy/fukushima_2012/pdfs/fukushima_iaea_en_06.pdf
[332] Practical Arrangements between the Ministry of Foreign Affairs of Japan and the International Atomic Energy Agency on Cooperation in the Area of Emergency Preparedness and Response (2012), http://www.mofa.go.jp/policy/energy/fukushima_2012/pdfs/fukushima_iaea_en_07.pdf

[333] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA and Japan Host Fukushima Ministerial Conference on Nuclear Safety (2012), https://www.iaea.org/newscenter/news/iaea-and-japan-host-fukushima-ministerial-conference-nuclear-safety
[334] Convention on Nuclear Safety, INFCIRC/449, IAEA, Vienna (1994).
[335] EUROPEAN ATOMIC ENERGY COMMUNITY, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, INTERNATIONAL MARITIME ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, WORLD HEALTH ORGANIZATION, Fundamental Safety Principles, IAEA Safety Standards Series No. SF-1, IAEA, Vienna (2006).
[336] Convention on Nuclear Safety, Rules of Procedure and Financial Rules, INFCIRC/573/Rev.6, IAEA, Vienna (2015).
[337] Guidelines Regarding the Review Process under the Convention on Nuclear Safety, INFCIRC/571/Rev.7, IAEA, Vienna (2015).
[338] Guidelines Regarding National Reports under the Convention on Nuclear Safety, INFCIRC/572/Rev.5, IAEA, Vienna (2015).
[339] 2nd Extraordinary Meeting of the Contracting Parties to the Convention on Nuclear Safety: Final Summary Report, CNS/ExM/2012/04/Rev.2 (2012), http://www.iaea.org/sites/default/files/cns-summaryreport310812.pdf
[340] 6th Review Meeting of the Contracting Parties to the Convention on Nuclear Safety: Summary Report, CNS/6RM/2014/11_Final (2014), http://www-ns.iaea.org/downloads/ni/safety_convention/2014-cns-summary-report-w-annexes-signed.pdf
[341] Summary Report and Vienna Declaration on Nuclear Safety, CNS/DC/2015/3/Rev.2 (2015), https://www.iaea.org/sites/default/files/cns_summary090215.pdf

ABBREVIATIONS

µGy	microgray
µSv	microsievert
AC	alternating current
ALPS	Advanced Liquid Processing Systems
ANRE	Agency for Natural Resources and Energy
Bq	becquerel
BSS	Basic Safety Standards
CI	confidence interval
ConvEx	Convention Exercises
CRIEPI	Central Research Institute of the Electric Power Industry
CSC	Convention on Supplementary Compensation for Nuclear Damage
DC	direct current
EC	European Commission
EDG	emergency diesel generator
ENATOM	Emergency Notification and Assistance Technical Operations Manual
EPZ	emergency planning zone
ERSS	Emergency Response Support System
FAO	Food and Agriculture Organization of the United Nations
FW	fresh water
GPD	general psychological distress
Gy	gray
HP	hold point
HPCI	high pressure coolant injection
IACRNE	Inter-Agency Committee on Radiological and Nuclear Emergencies
IC	isolation condenser
ICRP	International Commission on Radiological Protection
IEC	Incident and Emergency Centre
IEM	International Experts Meeting
IES	Incident and Emergency System
IGP	Institute of Geodesy and Photogrammetry
ILO	International Labour Organization
IMMSP	Institute of Mathematical Machines and Systems Problems
INES	International Nuclear and Radiological Event Scale
INPO	Institute of Nuclear Power Operations
INSAG	International Nuclear Safety Group
IRRS	Integrated Regulatory Review Service
IRSN	Institut de radioprotection et de sûreté nucléaire (Institute for Radiological Protection and Nuclear Safety)
JAEA	Japan Atomic Energy Agency
JAMSTEC	Japan Agency for Marine–Earth Science and Technology
JCNER	Joint Council for Nuclear Emergency Response
JCO	Japan Nuclear Fuels Conversion Company
JCOPET	Tide-resolving regional nested subsystem of Japan Coastal Ocean Predictability Experiment
JKEO	JAMSTEC Kuroshio Extension Observatory
JMA	Japan Meteorological Agency
JNES	Japan Nuclear Energy Safety Organization
JPLAN	Joint Radiation Emergency Management Plan of the International Organizations
JST	Japan Standard Time
KEO	Kuroshio Extension Observatory
KIOST	Korea Institute of Ocean Science and Technology
KNOT	Kyodo North Pacific Ocean Time-series

Kobe U	Kobe University
Local NERHQ	Local Nuclear Emergency Response Headquarters
MAFF	Ministry of Agriculture, Forestry and Fisheries
METI	Ministry of Economy, Trade and Industry
MEXT	Ministry of Education, Culture, Sports, Science and Technology
mGy	milligray
MHLW	Ministry of Health, Labour and Welfare
MITI	Ministry for International Trade and Industry
MO	motor operated
MOD (SDF)	Ministry of Defense (Self-Defense Forces)
MOE	Ministry of the Environment
MPa	megapascal
MSSG	Multi-Scale Simulator for the Geoenvironment
mSv	millisievert
NDF	Nuclear Damage Compensation and Decommissioning Facilitation Corporation
NERHQ	Nuclear Emergency Response Headquarters
NIES	National Institute for Environmental Studies
NIRS	National Institute of Radiological Sciences
NISA	Nuclear and Industrial Safety Agency
NPP	nuclear power plant
NPP-ERC	Fukushima Daiichi Emergency Response Centre at the NPP
NPS	Nuclear Power Station
NRA	Nuclear Regulation Authority
NSC	Nuclear Safety Commission
OECD/NEA	OECD Nuclear Energy Agency
OP	Onahama Port
PAHO	Pan American Health Organization
PBq	petabecquerel
PCV	primary containment vessel
PSA	probabilistic safety assessment
PTSR	post-traumatic stress response
RANET	Response and Assistance Network
RAPs	reference animals and plants
RCIC	reactor core isolation cooling
R&D	research and development
REMAT	Radiation Emergency Medical Assistance Team
SPEEDI	System for Prediction of Environmental Emergency Dose Information
Sv	sievert
SW	sea water
TEPCO	Tokyo Electric Power Company
TEPCO HQ-ERC	Emergency Response Centre at TEPCO Headquarters
UNEP	United Nations Environment Programme
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
USDA	United States Department of Agriculture
USGS	United States Geological Survey
UTC	Universal Time Coordinated
WHO	World Health Organization
WHOI	Woods Hole Oceanographic Institution
WMO	World Meteorological Organization

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MEETINGS

Working Group (WG) meetings

18 March 2013
Initial meeting of the WG Co-Chairs, Vienna

21–22 March 2013
1st meeting of all WGs, Vienna

12–14 June 2013
2nd meeting of all WGs, Vienna

12–13 September 2013
3rd meeting of WGs 1 and 2, Vienna

7–9 October 2013
3rd meeting of WGs 3, 4 and 5, Vienna

9–13 December 2013
4th meeting of all WGs, Vienna

10–14 February 2014
5th meeting of all WGs, Vienna

14–17 April 2014
6th meeting of WGs 1, 2 and 3, Vienna

5–9 May 2014
6th meeting of WG 4, Vienna

26–30 May 2014
6th meeting of WG 5, Vienna

International Technical Advisory Group (ITAG) meetings

21–22 March 2013
1st ITAG meeting, Vienna

10 June 2013
1st Joint ITAG/Co-Chairs meeting, Vienna

11 June 2013
2nd ITAG meeting, Vienna

6 December 2013
2nd Joint ITAG/Co-Chairs meeting, Vienna

7 May 2014
3rd Joint ITAG/Co-Chairs meeting, Vienna

23–24 October 2014
4th Joint ITAG/Co-Chairs meeting, Vienna

23–24 February 2015
5th Joint ITAG/Co-Chairs meeting, Vienna

Consultants services (CS) meetings

6–7 August 2013
CS on Source Term, Vienna

29–31 October 2013
CS on Human and Organizational Factors and Safety Culture, Vienna

17–21 November 2013
CS on Human and Organizational Factors and Safety Culture, Atlanta

13–17 January 2014
CS on Human and Organizational Factors and Safety Culture, Vienna

17–21 March 2014
CS on Human and Organizational Factors and Safety Culture, Ottawa

24–26 March 2014
CS on Radioactivity in the Environment, Monaco

20–21 May 2014
CS on Radiation and Log-Normal Distributions, Vienna

23–27 June 2014
CS on Radiation and Log-Normal Distributions, Vienna

Bilateral meetings in Japan

14–21 October 2013
Bilateral Discussions on Issues Related to the IAEA Report in the Area of Remediation

25–27 November 2013
CS to Discuss Issues Related to Radiological Consequences in Connection with the Preparation of Chapter 4 (Radiological Consequences) and Chapter 5 (Post-accident Recovery)

25 November–4 December 2013
Bilateral Discussions on Issues Related to the IAEA Report in the Area of Decommissioning

20–24 January 2014
CS to Discuss Issues Related to Regulatory Activities, Operating Experience and Waste Management Topics in Connection with the Preparation of the IAEA Report

23 January 2014
Meetings with Reconstruction Agency and Team in Charge of Assisting the Lives of Disaster Victims — Cabinet Office

24 January 2014
Meetings with the Institute of Energy Economics of Japan

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